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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Situational Awareness in Aerospace Operations

(La Perception de la Situation au cours des Operations Aériennes)

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.478

Situational Awareness in Aerospace Operations

(La perception de la situation au cours des operations aériennes)

Papers presented at the Aerospace Medical Panel Symposium held in Copenhagen,
Denmark, from 2nd—6th October 1989.

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- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;
- Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
- Exchange of scientific and technical information;
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Preface

Advances in aircraft system technology, the greater speed and manoeuvrability of combat aircraft, the increased complexity and sophistication of the projected combat environment, together with an increased amount of information presented to the pilot, has led to new demands on him. These factors are added to the classical environmental changes which fighter pilots already had to face in the past. In order to respond appropriately, a high level of situational awareness has to be maintained.

Aviators' situational awareness in this context is a cognitive state that is a combination of two items, namely:

- tactical awareness, that means an awareness of the constantly changing threat environment, and
- spatial orientation, meaning an awareness of the constantly changing aircraft orientation and position in space.

In order to review the developments and research activities which are related to situational awareness in the NATO countries, the AGARD Aerospace Medical Panel has initiated this Symposium. Many topics were considered. These included:

- Definition of conditions which may lead to loss of pilot situational awareness;
- Methods to assess situational awareness, both in the laboratory and in flight;
- Presentation of information in the cockpit;
- Perception of information, aircrew performance and training methods.

Some of the data and conclusions presented at this Symposium are of a preliminary nature and indicate that further research is needed. Furthermore there is evidence that human factors are still not considered sufficiently during the design stage of advanced fighter aircraft cockpits. It is hoped that the information provided in this volume will be introduced into future aircraft technology and flight procedures and thus satisfy the needs of the NATO countries.

* * *

Les progrès réalisés dans les technologies des systèmes avioniques, la vitesse et la maniabilité accrues des aéronefs de combat, la complexité et la sophistication toujours croissantes de l'environnement de combat des scénarios de guerre, et le volume accru d'informations présenté au pilote ne font qu'alourdir sa charge de travail. En outre, tous ces éléments sont à ajouter aux modifications classiques de l'environnement de l'aéronef que les pilotes de chasse ont déjà affrontées dans le passé.

Dans ces conditions, le pilote doit maintenir sa perception de la situation à un très haut niveau s'il veut fournir une réponse appropriée.

Vue sous cet angle, la perception de la situation par l'aviateur est un état cognitif composé de deux éléments, à savoir:

- la sensibilité tactique, c'est à dire la perception de l'environnement de la menace, qui est en constante évolution,
- l'orientation spatiale, c'est à dire la perception de l'orientation et de la position de l'aéronef dans l'espace à tout moment.

Le Panel de Médecine Aérospatiale de l'AGARD a organisé ce Symposium pour faire le point des développements et des activités de recherche relatifs à la perception de la situation qui sont en cours dans les pays membres de l'OTAN. De nombreuses questions ont été traitées lors du Symposium, parmi lesquelles on distingue:

- la définition des conditions qui risquent de conduire à une dégradation de la perception de la situation voire même à la perte de connaissance,
- les méthodes d'évaluation de la perception de la situation, tant en laboratoire qu'en vol,
- la présentation des informations au pilote,
- la perception des informations, les performances des équipages et les méthodes d'entraînement.

Certaines affirmations ou conclusions présentées lors du Symposium seraient de nature préliminaire, appelant ainsi des travaux de recherche plus approfondis et ceci d'autant plus que la preuve existe que les facteurs humains ne sont pas suffisamment pris en considération lors de la phase d'études des postes de pilotage des avions de combat de technologie avancée.

Il est à espérer que les informations contenues dans ce volume seront incorporées dans les futures technologies aéronautiques, ainsi que dans les procédures de vol, afin de répondre aux besoins des pays membres de l'OTAN.

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OPENING CEREMONIES

Major General Knud JESSEN, M.D., D.A.
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Mr. Chairman, distinguished colleques, ladies and gentlemen.

On behalf of the Chief of Defence it is my privilege to welcome all of you to Copenhagen to this AGARD/AMP symposium on SITUATIONAL AWARENESS IN AEROSPACE OPERATIONS.

It is, however, much more than a privilege to welcome you: it is a very personal pleasure to see so many good colleagues and friends in my own city - and to have especially this topic on the agenda.

Probably due to my rather heavy background in the clinical part of medicine it has always been obvious to me that an AEROSPACE MEDICINE PROGRAM should promote and maintain physical and mental development, health, and survival (which is the definition on ENVIRONMENTAL HEALTH made by WHO).

In other words: AEROSPACE MEDICINE should primarily be concerned with our clients' state of complete physical, mental and social well-being - and not merely the presence or absence of disease or infirmary.

So, talking about pilots, AEROSPACE MEDICINE basically concerns itself with the effects of the aerospace environment on pilot performance. The interaction between the pilot and his work environment has to be studied. The human factors, human possibilities, capabilities, and limitations on one side; the milieu, technical and physical, on the other. This is also called the MAN/MACHINE INTERFACE.

This possible controversy began already - more than 10 years ago - to create anxiety and worry due to a possible lack of balance between the human capabilities and the demands to this performance while working in the cockpit in the future high performance fighters. Would the pilot be the limiting factor? Would we have to look for some super-creatures at the selections?

Everybody knows that our high performance fighters are still flown by men. But it is also known that the development has imposed a tremendous workload on these pilots. Both physical and psychological. And the aerospace medical field has had to deal with this development, this new challenge to our profession.
This e.g. can be seen, if you read the topics discussed at the AEROSPACE MEDICAL PANEL MEETINGS of AGARD during these last 10 years: A development of the issues of interest from more traditional topics to highly complex areas with contribution of authors and institutions from the non-medical, highly technological world around aviation.

Is the pilot the limiting factor in high performance fighter operations? Is he too limiting today? Is the machine too complex for a human to cope with?

The former Director of AGARD, Dr Irving Statler, presented last year a briefing to the Military Committee of NATO on this topic. On the modern air combat putting enormous stress on the pilot's ability to absorb and manage information from multiple sources: radar, electronic warfare systems, the Joint Tactical Information Distribution System and so on. His concern was and is for the working environment of the modern military pilot and for the ability of this man/machine system to perform its assigned mission. In particular for the European scene of air operations which is characterized as a highly sophisticated threat environment, mostly in bad meteorological conditions, and over all kinds of obstacles. The pilot must fly low and fast to survive, exposing himself to high G-forces imposed him with a very high rate of onset, he is almost exclusively occupied with the tasks of flight path control or of monitoring the performance of a terrainfollowing system. Nevertheless, the pilot must still monitor flight data, aircraft systems, fuel management and navigation; the status of threats and the tactical situation. He must also perform tasks including management of electronic countermeasures, weapons, communications, and target-identification and designation systems.

During a brief period of time, all of these functions must be carried out simultaneously. But, some of them require the pilot to view the outside scene while others require his attention to the cockpit displays.

The role of the flight surgeon in future aerospace medicine is as complex as future fighter aviation. The clients of the flight surgeon will be specialists in a very technological and sophisticated environment imposing a lot of mental and physical stress - while airborn or on ground. The pilots will be confronted with teams of technologists, engineers, and physicians, who together will try to create the most effective man/machine interaction: a weapon platform.

The very rapid evolution in aviation through the last 10 years has moved the aerospace medicine from matters dealing with traditional medical work to a complex where our client - the pilot - easily can be a victim of the environmental threat and stress. He will be a part of the man/machine program, a controller of a weapon platform and as such confronted with teams of planners, designers, engineers, etc.

Aerospace medical research endeavors to investigate the very limits of human tolerance to the environment created by advanced aerospace engineering. The foremost aim of this medical research is to enhance performance and ensure the safety of the crews exposed to the environments that exceed human tolerance.

But as long as the pilot is a human, the flight surgeon will also be responsible for his health - which as mentioned means his state of physical, mental, and social well-being. The vast development in technology has not changed the principles of the WHO declaration. Aerospace Medicine will protect the pilot against being not only the limiting factor of the weapon platform - but even the looser in this game.

As written in the theme for this meeting, "Aviator situational awareness is a combination of tactical awareness and spatial orientation. In order to respond appropriately, combat aviators must maintain a high level of situational awareness.
Innovative basic and applied research being carried out on this topic is giving new insight which will result in improved information presentation and thus make optimal use of human information processing and decision-making capabilities".

It is more important than ever that the flight surgeons role in this research is implemented in the entire system through all possible channels in order to secure the biological interest of the human in this technological world.

I wish the Aerospace Medical Panel of AGARD good luck with this challenge and - certainly - you all a very good week in Copenhagen.

SITUATIONAL AWARENESS IN AEROSPACE OPERATIONS ONLY A PILOT's CHALLENGE?

by

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Since man realized that birds could fly, he has wanted to do so himself. It took us thousands of years to get there, and ever since we learned the basics - and understood the basics behind the basics - the development in aerospace operations has been overwhelming. Normally we want evolution - in order to be able to master development. Within the field of aerospace we have been forced to accept revolution in order to cope with the progress in aviation at large. It took less than 75 years to go from the first flight of man and onto the first human step on the surface of the moon.

This development is really astonishing and to be honest - also slightly frightening. Can we keep up the pace and hopefully keep the human being on top and thereby ahead of the developments in aerospace activities, not least in aerospace medicine? The keynote address to this symposium will center on the way ahead. The experts have learned a lot from history. We have to preserve all this knowledge and transform it beyond our present state of the art to make sure, that the aerospace establishment, including all the players from scientists to amateur pilots, will be able to cope with the situation - no matter if it is a question of safe passenger transportation or efficient military air operations in order to maintain peace and democracy.

Aerospace operations have now evolved so far that people who fear flying, must fly anyway, if they want to be full members of modern society. Aerospace operations are part of daily life and almost any kind of military operation. Aerospace operations are vital for environmental, scientific and space exploration purposes, and they constitute a substantial amount of public and private spending.

Looking ahead - and looking at the AGARD overall objectives - the subject of this symposium seems to be extremely relevant.

"SITUATIONAL AWARENESS IN AEROSPACE OPERATIONS" touches on probably the single most important issue of all - common to us all, regardless of education, rank and occupation. If the players involved in aerospace operations are not aware of their own and their fellow operators' situation - disaster is just around the corner.

For a great many years a substantial amount of effort was concentrated around making objects fly. Thereafter it became quite clear, that it took a great deal of skill and talent to fly these objects.

As flying developed into what we know today, we also learned that there is no easy way to safe and efficient aerospace operations. The accident records are enormous. The challenge of leaving "terra firma" in the early days seems to have had its own law of gravity. Nobody - or more correctly few - accepted that it took more than talent (and a pood portion of luck) to operate in the aerospace environment.

However, since the beginning of flight, mankind has slowly learned to adjust to the enormous challenges of operating airplanes and spacecraft. The responsible organizations have put a considerable effort into training talented pilots to become efficient commanders of reliable aircraft, be they civilian or military.

It is interesting to note the evolution in pilot selection procedures. During the last twenty years the leading nations within this field have been able to improve the prodecures to almost perfection. In the Royal Danish Air Force the failure rate of pilots that have passed the initial selection process is close to 5%, which is extraordinary considering the problems involved. However, we must all realize that the real challenge lies ahead, when the training system has to turn the remaining 95% of the student pilots into safe and efficient operators.

ABILITY (TALENT)

The initial selection process might be characterized as the measurement of basic knowledge and ability - or talent - to go through the whole process of pilot training with a high probability of success, including long term efficiency and survival rate. We rate not only the handling skills, but also deeper emotional and personality characteristica in order to assure a high degree of success, both for the organization and for the individual. A good example of just one very important factor, that has been become increasingly important, is the ability to reject applicants with no or little sense of fear. In the early days this kind of person was estimated to be the best type of candidate for pilot training. Now we know that a fearless pilot is a menace to his own and everybody elses' safety.

TRAINING

It is probably unnecessary to spend much time on the importance of training. In our day and age it is generally accepted, that it takes a lot of effort and concentrated training to become efficient in aerospace operations. The basics to build on is a certain amount of knowledge and ability - or talent - as described above. However the training system has become a very sophisticated one, capable of exploiting and developing the talent within a rather short span of time, so that the combination of talent and training evolves into the basic skill of flying.

PHYSICAL ENVIRONMENT (MAN/MACHINE/MAN)

The basic flying skill will not bring anybody - anywhere - anytime - unless it is put to use in a proper man/machine interface, which provides the operator with the physical environment necessary for on time - day or night - delivery of passengers, weapons or maybe spacecraft or satellites. What is the perfect man/machine interface? Haven't we developed the machines to perfection? Maybe so.

But have we been able to develop ourselves to cope with the almost perfect machines? These are extremely important factors in our dealing with aerospace operations approaching year 2000. A keynote address is too short to give a lot of answers, but long enough to raise a few questions.

How are we going to preserve and maintain the basic flying skills in our new generation of pilots flying airline and air force "electric jets"? How will those pilots perform in an emergency if they have to fly the good old manual way (no autopilot etc.)? How are the crews going to perform when all the old airline captains have retired, with new young captains having non-experienced co-pilots with a grand total of approximately 300 flying hours? How will the air force pilots be able to keep on going in the 9-G environment? Do the scientists and engineers really understand the needs and limitations of the operators? These questions are great challenges to pilots, but probably even greater to a lot of other people involved in aerospace operations.

For future work in this field it will be necessary to emphasize the man/machine interface more as a man/machine/man interface, thereby indicating that there is a third party in the relationship, namely all the people not directly involved in operating the machinery. The human beings involved must be able to work together and "understand" what is going - and what is not going - on.

PSYCHOLOGICAL ENVIRONMENT (MAN/MAN/MAN)

We are able to recruit sufficient people that possess the required amount of ability. We have developed training systems and created physical environments almost to perfection, but all these efforts will be to no avail, unless the individuals involved are working in a proper psychological environment.

We can measure, test and evaluate talent, skills and man/machine/man interfaces to a very large extent, which gives us a good background for improvements and refining of hardware and procedures. However, it must be realized that by far the most complex and unpredictable factor in the equation that leads to efficient and safe aerospace operations is missing, namely the human being. The strongest computer of all - the fragile human mind, which is utterly strong in the right type of psychological environment, and correspondingly weak when emotions, lack of concentration, complacency - a multitude of factors - may suddenly degrade performance to a critical level.

This is the real issue facing the symposium. This is the key factor - around which a major part of all thinking in this very important panel of the AGARD should concentrate. How do we create a psychological environment that leads to a fruitful exploitation of all our knowledge and advances in the field of human ability, training systems and man/machine/man interfaces? I postulate that the overall answer to this question is the very subject of this symposium:

SITUATIONAL AWARENESS
IN
AEROSPACE OPERATIONS

The subject is fundamental in all our endeavours to reach the common goal of safe and efficient operations.

Therefore, - as the keynote author - I find, that the subject of the symposium is a really brilliant one. I find that this title could be the basic general title for all meetings and symposia in the AGARD panel of aerospace medicine. Even if we all are aware of our own situation, we might not possess what is really incorporated into the expression "situational awareness". The span and scope of this expression is a delicate and intriguing intriguing one. It contains so much that it is hard to come to grips with it. In the Danish language we lack a proper translation. As with quite a few other expressions related to the sciences of aerospace, the English expression is by far the best.

What does it take to be able to be in control of the situation? It takes "a person" with a good deal of knowledge, ability and training in order to use the machinery - in the physical environment provided - which will only be possible if the human being performs in a proper psychological environment, as has already been touched on before.

Figure 1. illustrates the total capacity of a "situational awareness system" related to one single person as indicated by the solid square. The interrelationship between the main areas discussed earlier is demonstrated by the arrows leading from ability through to psychological environment.

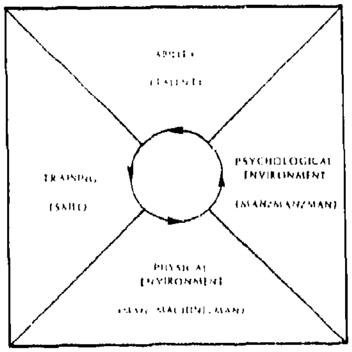

Figure 1

It should be noted that while a direct relation exists between ability, training and physical environment, there is no direct link between these three areas and the psychological environment. This phenomenon is illustrated in fig. 2, which shows that within a given total capacity, it is possible to compensate lack of training with a greater than normal inherent ability (or vice versa).

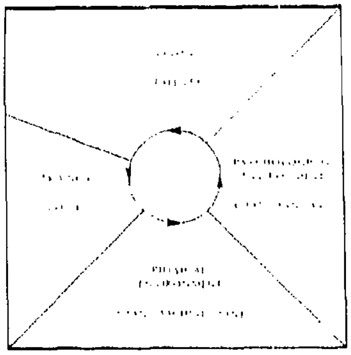

Figure 2

The same relationship is apparent between training and physical environment as shown in fig. 3, which indicates that a less than optimum physical environment can be compensated by extra training (or vice versa).

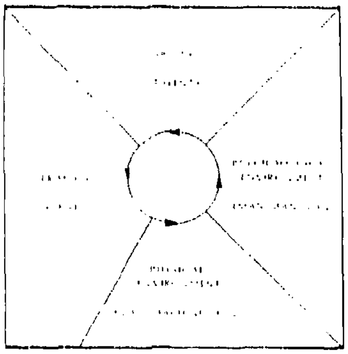

Figure 3

As mentioned earlier the psychological environment is not directly linked to either ability or physical environment - in other words a less than optimum psychological environment cannot necessarily be compensated by above average ability or a perfect man/machine/man interface. However, it must be realized that a break-down in the psychological environment might indirectly lead to an instantaneous disability (break-down or destruction of talent and/or skill), possibly causing disastrous chains of events - ultimately fatal accidents. On the contrary a person in an optimum psychological environment - a person in possession of situational awareness - will in many circumstances be able to compensate for flaws or break-downs in the other three areas.

It goes without saying that a lot of effort must be put into the "situational awareness" part of our understanding of our own situation and that of our fellow operators, be it directly related to aerospace operations or equally important the research, planning and production in support of such operations.

It follows from the earlier discussion, that while it is possible to compensate for weaknesses or strengths in ability, training and physical environment, the psychological environment is much more of a stand-alone area. With the revolution in aerospace in mind, we must realize that it is utterly important to stay on top concerning situational awareness. This is the only way to maintain control. We must strive to improve the situational awareness field by "expanding the single person total capacity".

This expansion is illustrated by fig. 4.

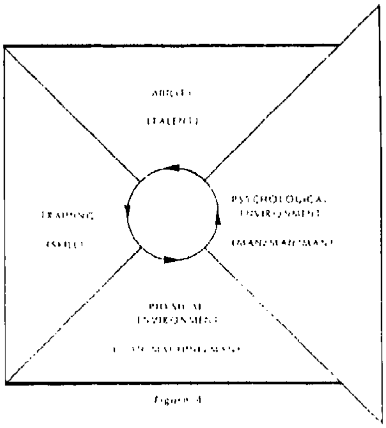

Figure 4

It is my opinion, that the expansion as illustrated, should not be regarded as an indication of add-ons but rather as an expression of better exploitation of already inherent capabilities, thereby improving the overall situational awareness.

What should we be looking for when developing the ability to attain and maintain situational awareness? The terrifying answer could very well be: Everything. The task is theoretically almost impossible, but fortunately we are dealing with the immense capability of the human mind. Experience has shown that we can get quite close to mastering situational awareness, but it takes a lot of listening, a lot of discipline and a lot of co-operation between individuals involved.

Even though it is hard to spell out the main issues involved in defining situational awareness, I dare suggest the following list as good examples of some of the more important ones:

- Listen to experience.
- Keep priorities clear in relation to task.
- Use common sense and sound judgement.
- Know own limitations (stop before exceeding).
- Set the example.
- Be aware of other individuals' situation and limitations.
- Be fit for task.

As can be seen the subjects almost exclusively fit into the psychological environment and they are thereby heavily dependent on the man/man/man interface.

Situational awareness in aerospace operations has normally been related to flying operations. But honestly - is it only a pilot's challenge? I postulate: Certainly not. We are all equally involved. You as well as I have to maintain situational awareness. We are basically all in the same boat as the operational aviators and spacefliers. The immediate and personal consequences of losing situational awareness might obviously be much more disastrous for the pilots, but could disaster be a result of some of us having lost situational awareness in our capacity as scientists, medical officers or ordinary staff officers? The answer might very well be: Yes, we could be directly responsible. By the way, have YOU ever driven a car, knowing very well that YOU were too tired to drive? Probably; in that case situational awareness was apparently lost.

Situational awareness is a challenge for every single individual involved in the endeavours to develop and sustain safe and efficient aerospace operations. Let that challenge lead us on through this symposium and into our future work within the auspices of the Aerospace Medical Panel and the overall objectives of AGARD and NATO as a whole.

Les déterminants de l'appréciation de la situation tactique et le développement de systèmes d'aides ergonomiques.

Factors involved in tactical situation awareness and the future of support systems.

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Summary : The paper presents a review of Tactical Situation Awareness (TSA) studies and discuss some possibilities to support the pilot in the assessment of TSA by the mean of computer-aids. It is divided into four sections: (i) an introductive discussion highlights some differences between the concepts of spatial orientation (static & absolute references to upright and horizontale), situation awareness (absolute geographical references and dynamic evolution of the process) and tactical situation awareness (relative position of threats and dynamic evolution of the situation), (ii) thus, a short review of the various factors involved in TSA is presented (iii) in order to propose a model of tactical situation awareness ; (iiii) The paper concludes with the description of some current or future ergonomic systems capable of improving the tactical situation awareness. Special attention is also paid to training improvements.

An extended english abstract is included at the end of the paper.

1-Introduction

Les futurs avions de combat voleront plus vite, plus bas, par toutes conditions météorologiques ou nycthémérales. Ils seront dessinés pour faire face à des contextes opérationnels et tactiques de plus en plus complexes, notamment en Centre -Europe (rapport de force de 1 à 6 , peut-être 1 à 10, menaces sol et menaces air très nombreuses avec partenaires et alliés mélangés à ces menaces) (**Symposium Agard GCP-FMP 1988**).

Dans cette situation, déjà partiellement existante, le rôle du pilote sera considérablement transformé (**Menu & al, 1988**) :

- Il touchera de moins en moins aux commandes de vol;
- il supervisera les automates chargés de l'assister dans la conduite des systèmes (en fait, cette supervision sera plus réduite qu'on ne peut le penser tant les automates sont complexes et empruntent des raisonnements non familiers par rapport aux raisonnements humains);
- enfin et surtout, il décidera des choix stratégiques et tactiques, il choisira les alternatives ; c'est là la véritable justification de son maintien à bord.

L'analyse est banale, le constat mille fois répété en aéronautique (**Morishidge, 1988; Smith & ,1988; Wiener, 1989; Amalberti, 1989**): L'évaluation de la situation tactique sera un élément clé-sinon l'élément clé-du succès des missions opérationnelles de l'an 2000 ; elle expliquera presque toute la variabilité inter-pilotes, tous les autres éléments du vol étant nivellés par une technologie somme toute comparable d'un pays à l'autre et d'un avion de même génération à l'autre.

Pourtant, alors même qu'un nombre considérable d'études restent développées sur le concept général d'orientation spatiale (ou à sa perturbation sous forme de désorientation spatiale), peu d'études sont consacrées à la prise de conscience de la situation dans l'espace et encore moins d'études concernent le concept de prise de conscience tactique de la situation. Tout se passe comme si le premier de ces concepts (orientation spatiale) était la traduction scientifique exclusive du second (prise de conscience de la situation) et que le fait de rajouter le terme de "tactique" ne change pas grand chose à cet état de l'art.

Une analyse simple des facteurs mis en jeu démontrent toutes les ambiguités de ce réductionnisme scientifique.

L'orientation spatiale, repose sur la capacité de réaliser un positionnement par rapport à un référentiel fixe : les directions verticales et horizontales de l'espace. Cet espace est lui-même référencé de façon fixe par la terre. Les études menées dans ce domaine se réfèrent à la prise d'information visuelle et aux interactions oeil-vestibule. La capacité d'orientation suppose le maniement par le pilote d'un modèle de résolution des conflits perceptifs générés par les informations provenant de nos différents capteurs sensoriels. Ce modèle repose sur l' analyse de l'orientation spatiale pour un état momentané; en ce sens, il s'agit typiquement d'un modèle d'état (par opposition à un modèle continu et dynamique nécessitant l'intégration d'une succession d'états). On sait depuis **Witkin** que les fondements de ce modèle perceptif peuvent être interprétés dans des termes plus généraux, notamment sous forme de véritables styles cognitifs.

La prise de conscience de la situation repose sur la capacité à se positionner géographiquement par rapport à la terre et la capacité à comprendre l'évolution du processus. Elle suppose de la part du pilote la manipulation d'un modèle mental du processus; ce modèle résulte de la transformation des états en fonction du temps (modèle dynamique). Il est super-ordonné par rapport au modèle de l'orientation spatiale (le pilote peut-être correctement orienté par rapport à la verticale et à l'horizontale et malgrè tout être perdu !). Quand ce modèle est conforme au réel, on dit que le pilote a "compris" la situation. En retour, une bonne compréhension aide considérablement l'opérateur à résoudre les conflits sensoriels ponctuels (désorientations spatiales) générés par les situations aéronautiques (effet de feedback sur l'appréciation de la situation spatiale).

La prise de conscience de la situation tactique repose sur la capacité de se positionner par rapport à un référentiel relatif (les amis et les ennemis, compte tenu des buts poursuivis). L'analyse que le pilote doit conduire nécessite de raisonner sur des états dynamiques du comportement des objets contenus dans l'univers (modèle de comportement dynamique des objets de l'univers, encore appelé : modèle d'attentes ou "expectation model" dans la littérature). L'appréciation de la situation tactique nécessite le bon fonctionnement des deux niveaux précédents (appréciation de l'orientation spatiale et appréciation de l'orientation géographique dynamique), mais inversement ne les nourrit pas en retour (ou très peu); la compréhension de la scène tactique ne facilite pas l'appréciation de la situation spatiale, et ne change pas la compréhension de la situation géographique et de la trajectoire suivie par la machine. En bref, l'appréciation de la situation tactique, dans la mesure où elle est principalement référencée aux propriétés dynamiques des objets de l'univers (et non à la terre comme les deux premiers modèles), devient un tout autre objet d'étude, et implique sans-doute des aides à l'opérateur très différentes (type intelligence artificielle-copilote électronique).

Il convient également de souligner que tout avion, et même plus généralement tout mobile, pose les problèmes de situation spatiale. Ces problèmes peuvent être reconstruits au laboratoire et analysés selon les paradigmes expérimentaux classiques dans la mesure où il s'agit de conflits sensoriels taches-indépendants (au fait près que la neutralisation de la tache neutralise également les feedbacks sur l'appréciation de la situation spatiale provenant de la compréhension de la scène, feedback tout à fait déterminants en conditions habituelles).

Inversement la prise de conscience de la situation , et encore plus de la situation tactique, n'a pas de sens hors de la tâche. Les études de ces domaines sont donc nécessairement des études en situations naturelles, éventuellement des études en simulateurs de vol complets, mais en tout cas jamais des études de laboratoires. Les outils méthodologiques à mettre en place sont différents, les domaines scientifiques concernés sont également différents: psycho-physiologie, psychophysique, psychologie expérimentale dans le cas de l'évaluation de la situation spatiale, psychologie cognitive, ergonomie cognitive et modèles informatiques dans le cas de l'appréciation de la situation tactique. Rappelons encore que la prise de conscience de la situation tactique est particulièrement importante en aviation de combat mais qu'elle reste pertinente pour l'aviation civile, notamment pour les activités de vol à vue, d'anticollisions en vol et de trafic aéroport (taxi-way, parking).

La suite de ce texte reprend plus en détail les fondements des trois modèles décrits (§2) : modèles de la situation spatiale, du processus et de la situation tactique, avant d'en proposer un résumé fonctionnel (§3) et d'en examiner les conséquences en termes d'aides embarqués ou de programme de formation (§4).

2-Facteurs impliqués globalement dans la prise de conscience de la situation

2-1 Facteurs impliqués dans l'orientation spatiale

La tâche de pilotage n'est pas une situation naturelle pour l'homme. Elle implique des évolutions rapides dans un univers multidimensionnel. Il peut en résulter dans différentes situations des conflits sensoriels générant des illusions sensorielles ou même des désorientations spatiales voire même à l'extrême un véritable mal de l'espace.

Un constat doit être fait d'emblée: on parle beaucoup plus souvent de désorientation spatiale (analyse des facteurs perturbant l'orientation spatiale) que d'orientation spatiale (analyse des facteurs produisant l'orientation spatiale). Régulièrement des congrés **AGARD (CP 95, CP 287,** voir par exemple pour une revue de synthèse **Colin**, ou plus récemment les articles du **CP 433)** prenant pour théme les désorientations spatiales ou le mal de l'espace, évoquent quels en sont leurs retentissement sur le pilotage et présentent les moyens de les éviter ou de les contrer.

2-1-1 Mécanismes physiologiques de l'orientation spatiale, intermodalité sensorielle et facteurs perturbants

L'orientation spatiale, telle que nous l'avons définie précédemment, implique une perception de la verticale et de l'horizontale. En aéronautique comme sur terre, elle est basée sur des mécanismes psychophysiologiques qui peuvent être perturbés par différents facteurs externes. Ces deux aspects (conditions physiologiques et agressions spécifiquement aéronautiques) doivent donc être pris en compte.

Chez l'homme, l'orientation spatiale dépend de l'intégration de signaux issus de l'ensemble des systèmes sensoriels: le système visuel, le système vestibulaire, la proprioception, et à un niveau moindre l'audition. Alors que les yeux donnent une image tridimentionnelle de l'environnement, le système vestibulaire informe sur les mouvements linéaires ou angulaires de la tête. Les autres récepteurs de la proprioception donnent des informations sur la périphérie du corps. L'audition dont le rôle est limité sur terre dans les mécanismes d'orientation spatiale peut toutefois être utile en vol.

Depuis bien longtemps un concensus existe pour indiquer que la vision est le système sensoriel privilégié de l'orientation spatiale. Les réflexes posturaux et vestibulooculaires stabilisent l'image rétinienne. Ces mécanismes sont de plus en plus précisément étudiés, surtout si l'on envisage l'utilisation à l'avenir de visuels et viseurs de casque (e.g.interactions stimulations vestibulaire particulière sur des tâches de tracking visuel (**Leger & Sandor, 1988**).

Le vol ajoute aux modèles précédents la nécessité de prendre en compte les variations du facteur gravitationnel. Ces changements stimulent le système vestibulaire selon un mode inhabituel car non rencontrées pour un homme vivant sur terre. Ces stimulations vestibulaires inhabituelles peuvent être à l'origine non seulement de réflexes oculovestibulaires mais aussi d'une modification de la perception de la verticale (**Graybiel & al, 1979**).

2-1-2 Mécanismes normaux, Vision et orientation spatiale

La vision est avec le système vestibulaire l'un des deux systèmes indispensables pour le positionnement du corps dans l'espace. Le rôle respectif de la vision centrale et de la vision périphérique pour l'orientation dans l'espace doivent être envisagés selon un mode proche de celui que **Schneider (1958)** avait proposé et que **Leibowitz & Dighans (1980)** développaient pour l'aéronautique (congrés **AGARD** consacré aux désorientations spatiales).Toutes les études effectuées depuis ont précisé cette différence entre la vision centrale ("Focal mode") et la vision périphérique ("Ambient mode").

La vision périphérique est essentielle pour l'orientation spatiale du fait de la sensibilité particulière de perception des détails larges et du mouvement (**Menu, 1986**). Les détails les plus larges de l'image situent de manière comparative la position des objets dans l'espace. Pour la perception du mouvement il faut dissocier la sensation de mouvement égocentrique de la sensation exocentrique. Pour les sensations égocentriques, le sujet stationnaire "attribue" le mouvement aux objets et se sent immobile. Pour les sensations exocentriques de mouvement, le même sujet stationnaire, se sent en mouvement dans un environnement immobile. C'est la vection.

La vision centrale est comparativement beaucoup moins impliquée que la vision périphérique dans les mécanismes de l'orientation spatiale. Elle concerne plutôt le pouvoir de discrimination fin du système visuel (apprécié cliniquement par la détermination de l'acuité visuelle) et la perception de la verticalité (par association à des stimulations vestibulaires).

L'ensemble de cette perception du mouvement par le système visuel, l'influence de la vision centrale et de la vision périphérique, la pondération avec le système vestibulaire ont particulièrement bien été étudiés par une série d'auteurs comme **Reason & Brand (1975)**, **Brandt & al 1973**, **Bonnet (1982)**, **Johansson (1982)**, **Berthoz & al (1979)**. **Leibowitz & al. (1982)** ont essayé de synthétiser le rôle des connaissances les plus récentes sur le plan du système visuel dans la conduite d'un véhicule.

Toutes ces expérimentations ont été effectuées de manière isolée, abordée sur l'animal avec des études neurophysiologiques et chez l'homme avec des techniques psychophysiques (**Wertheim & al,1982**).

2-1-3 Intermodalités et facteurs modifiant l'orientation spatiale

L'influence et le rôle des autres capteurs sensoriels ont été étudiés soit isolément soit en interaction dans ces mécanismes d'orientation spatiale. Une abondante littérature décrit l'influence de ces différents capteurs (**Boff & al, 1986**). L'analyse des facteurs impliqués dans l'orientation spatiale telle que présentée dans l' "engineering data compendium" publié par **Boff & Lincion (1988)** montre l'existence d'un très grand nombre de facteurs associés: perception du mouvement, perception de la taille, de la forme, de la distance, localisation spatiale. Ces cinq rubriques ou grand thèmes de l'orientation spatiale sont décrits progressivement selon une structure emboitée. On aboutit alors à des descriptions très précises par le biais de résultats d'expériences de psychophysique sur l'homme de facteurs comme l'acuité stéréoscopique ou l'adaptation à des distorsions visuelles. Les résultats de telles études permettent de définir qu'en situation habituelle, la vision est la modalité sensorielle optimale pour donner l'orientation verticale du corps. Le système vestibulaire ne prend l'ascendance sur la vision que lorsque la vision ne remplit plus correctement son rôle (absence d'image ou image de mauvaise qualité).On aboutit alors à la description de situations conflictuelles sous forme d'illusions sensorielles à point de départ visuel ou vestibulaire.

Sur le plan de la physiopathogénie des désorientations spatiales rencontrées en aéronautique, **Benson (1984)** propose un modèle du contrôle moteur et du mouvement. Il utilise ce modèle pour expliquer l'apparition du mal des transports. Des structures neuronales qualifiées de "comparateur" ont pour objet de mettre en relation une trace mémorisée d'une situation avec ce qui est fourni par les systèmes sensoriels essentiels pour l'orientation, à savoir la vision, les canaux semicirculaires et le système otolithique. Un écart relativement important entre le pattern mémorisé et celui qui est fourni par les capteurs serait générateur d'une situation inhabituelle, pouvant produire les mécanismes de désorientation spatiale et à l'extrême le mal des transports.

En dehors des conflits intersensoriels, d'autres agressions physiques aéronautiques peuvent avoir un retentissement sur les mécanismes physiologiques de l'orientation spatiale. Sous accélération ou sous hypoxie, la vision périphérique sera la première touchée. Or nous avons vu son rôle essentiel. L'hypoxie peut même avoir un rôle global sur le système nerveux central et retentir directement sur les mécanismes de traitement d'information et de résolution de problème (comme l'évaluation de la situation tactique).

2-1-4 Perception de la verticale et style cognitif

Les psychologues expérimentalistes, particulièrement les Gestaltistes, ont également beaucoup apporté à la compréhension des mécanismes de perception de la verticale.Deux théories de perception de la verticale s'opposaient dans la période de l'immédiat après-guerre : celle donnant le primum à la référence visuelle et celle donnant le primum à la référence posturale. **Witkin (1959)** dans une expérience princeps (le sujet dans une chambre noire, assis sur un siège inclinable, avec face à lui un baguette située dans un cadre, doit la remettre verticale) montre que les deux théories sont valides : certains sujets se fient au barres du cadre pour aligner la verticale de la baguette (ils sont dits dépendants du champ visuel), d'autres sujets se fient à leurs sensations vestibulaires (il sont dits indépendants du champ visuel). Très rapidement, Witkin élargit sa théorie en montrant que les sujets dépendants du champ ont un véritable comportement général: la dépendance /indépendance du champ (visuel) (ou D.I.C.) est alors considérée comme un style cognitif. En 1962, **Witkin & al** complètent cette analyse en introduisant l'idée de différentiation psychologique : la différenciation caractérise les relations entre le sujet et le monde extérieur : le sujet est d'autant plus différencié (indépendant du champ) qu'il croit moins à ce qu'il voit dans le monde extérieur.

A ce jour, la littérature consacrée aux styles cognitifs est immense, très homogène quant aux aspects perceptifs, plus discutée quant aux incidences sur la personnalité (pour un point de vue complet, voir par exemple la synthèse récente de **Huteau (1985)**). En aéronautique (études cartographiques, (**Santucci & al (1961)**, **Papin & Valot (1983)** ou dans des tâches équivalentes (**Goodenough & al (1982)**, tâche de serveur de bitubes anti aérien, **Marandas & Ohlman** (en cours)) plusieurs auteurs ont repris ces travaux pour apprécier le rôle de la DIC dans les désorientations spatiales. Ces études montrent (i) que la DIC joue un rôle important comme facteur régulateur central au niveau de l'intégration inter-sensorielle (réglage et seuillage du comparateur dans un modèle de type **Benson (1984)**), (ii) que les pilotes de combat sont très souvent des personnes dites "indépendantes du champ"; ceci peut expliquer leur relative résistance à la désorientation spatiale par rapport à des non-pilotes placés dans les mêmes circonstances, (iii) c'est l'environnement, la culture et l'entrainement qui façonnent le degré de dépendance à l'égard du champ; il est également souligné que tout sujet utilise un mode préférentiel de fonctionnement (dépendant ou indépendant) mais est capable volontairement d'utiliser l'autre mode surtout s'il subit un entrainement spécifique pour cela.

2-2 facteurs impliqués dans la prise de conscience de la situation

La prise de consience de la situation est parfaitement assimilable à l'idée de compréhension de la scène: il s'agit pour l'opérateur de se dresser une représentation mentale correcte de sa position géographique actuelle et future compte-tenu du déplacement de l'avion.
Deux familles de facteurs peuvent donc être discutés dans ce cadre : (i) l'évaluation de la position géographique instantanée (navigation, cartographie), (ii) l'évaluation de la transformation future des états du fait du déplacement (modèle du processus).

(i) Evaluation de la position géographique

Cette activité repose sur la gestion du plan de vol et sur l'analyse de l'historique des faits survenus pendant la mission. L'historique des faits permet d'estimer les perturbations causées au plan de vol et d'en déduire une estimation relative de l'écart. L'introduction de centrales à inertie et de calculateurs de bord capables de travailler sur des points préparés à l'avance a bouleversé ce type d'activité dans la mesure où elle permet au pilote plusieurs degrés de liberté dans sa navigation. Avec de tels systèmes, sa position instantanée n'est plus référencée à la terre en projection verticale mais se trouve référencée dans un espace "horaire-vitesse à prendre-distance" à des points fixes eux mêmes clairement référencés à la terre (les points tournants); il s'agit ici d'une généralisation des aides à la navigation, jusqu'à présent limitées aux balises posées au sol. En bref, l'introduction de ces systèmes, tout en donnant au pilote une très grande marge de manoeuvrabilité de navigation, a pratiquement résolu les problèmes de référence géographique en en changeant leur nature. Il reste que la panne éventuelle de ces systèmes où une sortie prolongée de la route prévue (évasive tactique) peuvent ramener le pilote dans une situation de navigation manuelle. L'effet de l'assistance peut alors être pervers: **Amalberti & al (1987)** observent par exemple que les anciens pilotes continuent avec les nouveaux systèmes à utiliser en parallèle des procédures automatiques des procédures personnelles de navigation manuelles (recoupement divers, chronométrage des branches, utilisation de la carte 100.000° à bord, etc) alors que les jeunes pilotes ont tendance à ne plus pratiquer ces modes manuels, voire même à l'extrême à ne plus prendre de carte de navigation avec eux. C'est toute la relation de confiance au système qui est en jeu (**Valot & Amalberti, 1989**) et, en ce sens, cette dimension dépasse largement le cadre de l'appréciation de la situation pour atteindre celui de véritables styles de pilotage différents; les jeunes investissant plus de confiance dans les systèmes, mais les connaissant mieux également , utilisent souvent plus complètement que leurs anciens la haute technologie des avions modernes dans le combat; L'excès de confiance est la rançon de cette nouvelle répartition des ressources (et des rôles) dans le couple pilote-avion.

(ii) modèle du processus

L'idée que l'homme utilise pour conduire les processus une représentation mentale de l'évolution de la situation qui prend en compte les capacités et les limites de la machine est maintenant bien établie. On retrouve ce concept chez **Cuny & Deransart (1972)** avec la notion de "machine minimale" (ensemble minimal des variables d'un système qu'il suffit de connaître pour conduire le processus) ou encore chez **Moran (1981)** avec la notion de "grammaire limitée" pour la programmation (ensemble minimal de règles de grammaire utile pour programmer sur une machine donnée). On le retrouve également dans plusieurs expérimentations relatives à la tâche de programmeur (modèle de la calculette chez **Young,1981**):la logique technique de construction d'un système (ou logique du fonctionnement) peut être clairement différenciée de la connaissance que l'on doit posséder sur le même système pour l'utiliser (logique de l'utilisation) (**Richard, 1983**). Cette dernière connaissance est bien plus simple, finalisée par le but, permettant un guidage et une régulation des actions (utilisant des représentations opérationnelles, **Leplat, 1988**) et surtout procurant à l'opérateur une anticipation du comportement du processus. C'est typiquement ce type de représentation mentale que l'on appele modèle du processus .

En pilotage, cette représentation du processus est essentielle car elle fournit au pilote une anticipation sur les évolutions de trajectoire. Quand cette anticipation est correcte, les phénomènes de désorientations spatiales sont extrèmement limités.

Dans la très grande majorité des cas, la source des accidents graves réputés dus à un désorientation spatiale se trouve être la perte initiale de la compréhension de la dynamique de la scène (**Newman, 1980, 1988, Santucci & al, 1984, etc**), perte qui entraine secondairement une désorientation spatiale par défaut de référentiel qui en retour parasite encore plus le mécanisme de compréhension; parcequ'elles touchent à des problèmes cognitifs complexes, ces désorientations sont généralement de longue durée, et c'est bien la raison pour laquelle elles génèrent des accidents graves. Inversement, de nombreux incidents passagers et sans conséquence ont pour origine des conflits sensoriels instantanés, facilement résolus dès lors que le pilote possède une bonne compréhension de l'univers dans lequel il évolue.

Ainsi, en 1982-83, l'aéronavale Française perd 6 super-étendards en quelques mois. Ces avions sont les premiers avions Français dotés d'un collimateur tête-haute de pilotage. La première cause évoquée est la désorientation spatiale car plusieurs des accidents sont survenus en virage ou lors d'entrées en couches nuageuses. L'analyse (**Santucci & al, 1984**) montrera que ces accidents sont survenus avec des pilotes ayant déjà un passé aéronautique important, utilisant la VTH avec des comportements magiques (confiance excessive, manque total d'anticipation) et qu'ils se sont sont retrouvés désorientés parce qu'ils n'avaient pas compris la symbologie, du fait de leur inexpérience ou du fait d'un manque de doctrine dans l'utilisation du viseur (fort vent, entrée en couche nuageuse). La désorientation provenait (i) d'une mauvaise compréhension de l'information, puis de la situation, (ii) d'une décision de retour aux instruments classiques trop tardive, (iii)parce que cette décision était trop tardive, d'un basculement brutal de la tête alors que l'avion était déjà en évolution rapide, donc aggravation par un conflit sensoriel possible.

Enfin, l'ensemble des études montre clairement qu'en situation de combat aérien, le pilote anticipe grâce au modèle de processus qu'il possède, la trajectoire qu'il va réaliser. Pendant l'évolution, il se soucie en conséquence beaucoup moins de connaître son orientation précise, sachant que la manoeuvre engagée va le ramener dans une position non ambigüe. Les accidents surviennent quand le pilote ne peut pas réaliser la manoeuvre qu'il avait envisagée et donc se retrouve contraint d'évaluer son orientation spatiale pendant la manoeuvre sans anticipation.

2-3 Facteurs impliqués dans la prise de conscience tactique de la situation

La prise de conscience de la situation tactique peut-être définie comme la prise en compte des évènements et contraintes générées par le contexte et susceptibles de géner l'atteinte du but. Rappelons également que la tactique est définie en psychologie cognitive comme une procédure consciente, orientée vers un objectif précis (finalisée) et destinée à résoudre une situation problématique; le terme est voisin du concept de " stratégie" mais s'applique à des procédures de plus courte durée. L'élaboration de la tactique repose sur les attentes que l'on peut développer sur l'évolution de l'environnement. C'est à **Tolman & al (1946)** que l'on doit la première formulation d'une telle théorie des attentes (sign gestalt expectations theory). Actuellement, la notion d'attente est généralisée sous le nom de modèle d'attente (expectation model) ou modèle mental du monde environnant, véritable représentation cognitive de l'évolution des facteurs composants l'environnement. Ces modèles ont été particulièrement étudiés en linguistique et psychologie générale (logique des mondes possibles , en économie (théorie fiduciaire de l'adaptation aux variations de la bourse) et dans les jeux de guerres et les entrainements aux prises de décisions des décideurs des chefs militaires. Dans ces situations, comme en contrôle de processus, il apparait que les opérateurs humains catégorisent et hiérarchisent l'environnement en fonction du temps que mettront les différentes variables de l'environnement à les menacer. Cette catégorisation aboutit à une simplification des évènement possibles , avec des raisonnements basés sur un ensemble limité de facteurs et orientée à court terme (**Rouse, 1981; Amalberti & al, 1987**)

3-Vers un modèle de la prise de conscience de la situation tactique.

Les différents mécanismes et facteurs envisagés dans le paragraphe précédent peuvent être assemblés au sein d'un modèle heuristique de la prise de conscience de la situation tactique (figure 1). Un tel modèle permet sur un plan ergonomique de mettre en place les différents points où les systèmes d'aides pourront intervenir.

Le modèle présenté possède deux niveaux fonctionnels distincts :

-le premier niveau correspond à la compréhension de la scène et comporte en éléments de bases les mécanismes de l'orientation spatiale (selon le modèle heuristique de **Benson (1984)** enrichi des connaissances possédées sur les styles cognitifs). La compréhension résulte de l'analyse cognitive de données de différentes natures : suite d'états d'orientations spatiales, expérience sensorielle dans le domaine, connaissance des buts poursuivis,et connaissance possédée sur le fonctionnement de la machine. Ce modèle de compréhension de la scène , permettant au sujet de savoir d'où il vient et où il va (dans la mesure où il n'y aurait pas d'incident) peut-être représenté sous forme d'une architecture informatique de type "black-board" alimenté par les différents éléments envisagés précédemment. La sortie de ce niveau est double : interne et externe. Interne car la compréhension de la scène assure un feed-back sur les données nourrissant le blackboard, particulièrement les mécanismes de l'orientation spatiale; cette compréhension introduit ainsi une grande tolérance à l'erreur sur les problèmes de perception et de réglage du comparateur. Externe, elle nourrit partiellement le niveau de l'analyse tactique.

-le second niveau est celui de l'analyse tactique; il intègre les données de la compréhension de la scène à celles qui lui sont fournies par un modèle de comportement des objets de l'univers. Il nécessite également le recours à un modèle du processus pour sélectionner la bonne réponse en fonction des possibilités réelles de l'ensemble de la machine.

4-perspectives d'aides ergonomiques

4-1 problématique des aides

La structure même du modèle explicité dans les paragraphes précédents conduit à se poser la question "aides à quoi?": aides à l'orientation spatiale, aides à la perception de la situation ou aide à la perception tactique; à l'évidence il s'agit au moins pour le dernier cas de problèmes de nature assez différente:

-l'aide à la compréhension de la situation, par le très fort feedback existant sur l'orientation spatiale, devrait permettre une résolution rapide des conflits sensoriels; en ce sens, cette aide de niveau supérieur est à priviligier à une aide de premier niveau qui ne fait que régler les problèmes ponctuels d'orientation spatiale. Toutefois cette opinion peut-être pondérée dans les cas d'évolutions très rapide (type combat aérien) où le pilote peut trouver bénéfice d'une assistance à la perception de l'horizontale et de la verticale.

-L'aide à la perception tactique ne peut emprunter les mêmes voies. La perception tactique ne garantit en rien que l'opérateur ait une bonne représentation de son orientation spatiale (absence de feedback). Inversement, une bonne orientation spatiale, même s'il s'agit d'une condition nécessaire à une représentation tactique, ne saurait être une condition suffisante. Il faut développer des aides spécifiques à ce niveau et envisager de faire fonctionner des aides du niveau précédent et des aides de ce niveau de façon simultanée. Un problème de nécessaire homogénéité et d'intégration système est donc posé dans la conception générale de l'architecture de ces aides.

Le plan proposé découle de cette analyse. Il distingue pour chacun des deux niveaux les solutions existantes de celles qui pourraient être développées en accord avec les modèles et les facteurs analysés précédemment; dans tous les cas une part significative sera réservée aux actions de formation des pilotes.

4-2 Aides répondant à l'orientation spatiale et à la perception de la situation

4-2-1 Aides favorisant l'orientation spatiale

4-2-1-1 Actions sur les systèmes:

L'architecture des planches de bord actuelles, notamment avec l'introduction des VTH, répond à la nécessité de maintenir le pilote dans la boucle pour des domaines de performances de plus en plus élevés sous fort facteur de charge et lors d'évolutions rapides; il faut permettre au pilote de garder son regard sur le monde extérieur, à la fois pour lui éviter des transitions VTH-VTB, couteuses en temps et génératrices de conflits sensoriels, mais aussi pour des raisons tactiques (évolutions rapides de la situation extérieure). Une première solution est purement systémique (automate de remise à plat de l'avion); une deuxième solution consiste à optimiser la VTH ou/et à la compléter par d'autres dispositifs de présentation d'informations. Une troisième solution consiste à remplacer l'ensemble de la planche de bord par un viseur-visuel de casque.

(i) Sur certains avions russes, le pilote dispose d'un interrupteur coup de poing lui permettant en cas de désorientation spatiale une reprise en main automatique de l'attitude de l'appareil ramené alors en vol horizontal stabilisé. Un dispositif équivalent se retrouve sur toute la génération des pilotes automatiques modernes lors de l'enclenchement des modes supérieurs; il se retrouve également sous une forme de conseils dans certains indicateurs de sortie de vrille (e.g. F14). Ces dispositifs ont évidemment l'inconvénient d'interrompre brutalement la manoeuvre et d'être d'un intérêt tactique discutable; ils ne sauraient résoudre tous les cas où le pilote pourrait connaître des désorientations spatiales. D'une certaine façon ce type de système est une généralisation du filet de sauvegarde en version "temps de paix" qui ne se trouverait plus ainsi limité aux situations de pertes de connaissance mais étendu aux situations de pertes de cohérence.

(ii) L'optimisation de la VTH fait l'objet de nombreux travaux sur les symbologies: depuis plusieurs années **Newman** préconise l'utilisation de règles d'ergonomie générale maintenant bien acceptées par la communauté scientifique: utiliser autant que possible les symbologies analogiques, contrôler la densité de symboles, etc; plus spécifiquement, on rélève la création de symbologies spécifiques pour éviter la désorientation spatiale : mini-boule présentée en vision centrale sur le Rafale lors des évolutions rapides, adaptation de symbologies pour la vision paracentrale (élargissement des symboles au delà de 2° d'excentricité (**Mc Naughton, 1984**)), etc. A ce jour, quelle que soit l'ampleur de ces travaux, ils ne concernent que le renforcement de la perception spatiale en vision centrale et leurs approches ne peuvent être que ponctuelles puisqu'il n'existe pas de métrique de l'organisation dans l'espace de la stimulation visuelle (**Duval-Destin & Menu, Duval-Destin & al, sous presse**); or comme nous l'avons vu précédemment, l'orientation spatiale dépend en fait plus de la vision périphérique.

De là le développement d'autres aides spécialisées dans ce domaine et indépendantes de la VTH: l'horizon de **Malcolm (1983)** en est le plus connu. Il s'agissait d'utiliser la vision périphérique pour détecter l'horizon projeté dans l'ensemble du cockpit. Toutefois, cette tentative n'a pas été poursuivie car elle n'était pas parfaitement adaptée aux caractéristiques psychophysiologiques de la vision périphérique (lignes trop fines pour être percues). Depuis, d'autres travaux ont été conduits sur l'optimisation des symbologies à présenter en vision périphérique; ils restent toutefois du domaine du laboratoire car ils nécessitent le développement de procédés de visualisations tout à fait particuliers (projection sur verrière, visualisations latérales..) et non maitrisés technologiquement dans le cadre de l'intégration aux planches de bord actuelles.

En résumé, si l'on conserve les architectures actuelles des planches de bord, les aides à l'orientation spatiale ne se limitent plus à la simple optimisation du champ et de la symbologie de la VTH. Elles doivent concerner la création de symbologies périphériques avionnables. Tout reste à faire en ce domaine. Dans l'état actuel les efforts réalisés en vision centrale ne sont pas suffisant pour assurer en permanence un bonne orientation spatiale.

(iii) L'utilisation de viseur-visuel de casque est une solution plus ou moins complètement alternative aux systèmes de visualisations têtes haute. L'avantage réside dans le couplage et l'asservissement des visualisations aux mouvements de la tête qui libère le pilote des contraintes de transitions visuelles; sur le plan de l'orientation spatiale, ce type de système suscite plutôt plus d'inconvénients que les architectures classiques de planche de bord: couplage des caméras (asservissement entre la source image et sa restitution : déphasages possibles entre mouvements de la tête et mouvements des images), conflits d'horizon (découplage entre le pilote qui est libre de la direction du regard et son aéronef qui lui fournit un horizon calculé en position frontale), absence de repères cabines; **Papin & Menu (1983)** avaient montré la nécessité de ré-introduire des montants de cabine dans l'image d'un visuel de pilotage d'hélicoptère pour éviter les désorientations; pour les viseurs de casque, difficulté de couplage et d'intégration aux architectures classiques , particulièrement aux VTH (superposition de champs et de symbologie, d'où l'idée Américaine (Advanced Tactical Fighter) d'un "low level HUD" dont le champ est réduit verticalement (15°) .

Enfin, du fait qu'il n'existe pas encore de systèmes binoculaires opérationnels (il en existe en laboratoires) on est contraint dans cette solution viseur-visuel de casque à présenter l'information en monoculaire. Or ces systèmes monoculaires peuvent générer un conflit sensoriel entre les images prise en compte par chacun des deux yeux.

4-2-1-2 Actions de formation

L'entrainement classique au vol aux instruments reste d'actualité et demeure une des habiletés de base du pilotage; il perd cependant de l'importance avec le développement des VTH. Les formes modernes d'entrainement pour combattre la désorientation spatiale résident plutôt dans l'utilisation de dispositifs limités de simulation permettant aux pilotes de faire l'expérience sur commande de certains types de désorientations, sans toutefois pouvoir se raccrocher à une situation opérationnelle concrète (on neutralise les feedback liés à la connaissance de la situation aéronautique). C'est particulièrement le cas du Générateur d'Illusions Sensorielles (GIS) installé en France au Laboratoire d'Etudes Médico Physiologiques de Mont-deMarsan. D'autres systèmes de même ordre existent depuis plusieurs années dans différentes armées de l'air des pays de l'OTAN.

D'autres expériences, plus éloignées de la réalité journalière du vol, concernent l'entrainement des élèves ou des opérateurs à mieux connaître leur style cognitif (dépendant ou indépendant du champ visuel) et à globalement mieux interpréter les sensations visuelles. Des expériences de ce types ont été conduites en milieu scolaire avec des résultats plutôt contradictoires dans de nombreux laboratoires.

4-2-2 Aides à la perception de la situation

4-2-2-1 Actions au niveau des systèmes

Il s'agit ici de fournir au pilote des aides à la navigation et à l'évolution de la trajectoire. Il est clair que l'introduction de cartographie embarquée, couplée à des centrales à inertie représente une aide majeure en ce domaine.

Pour la gestion à court terme, par la sélection en modes automatiques, ces technologies permettent aujourd'hui des suivis de terrain automatiques qui paradoxalement résolvent les problèmes de localisation géographique alors qu'ils génèrent parfois des désorientations spatiales ou plus exactement des sensations de malaise lors du vol lui-même (découplage entre la logique et les réactions des automates et les procédures qu'auraient utilisées spontanément les pilotes dans les mêmes circonstances).

Pour l'anticipation à long terme, les systèmes cartographiques ne fournissent à ce jour que des indices à partir desquels le pilote établit sa représentation mentale; des progrès sont encore attendus dans la visualisation des déplacements grace à l'introduction de la troisième dimension, soit par rendu de l'image 2D (perspectives, dégradés de couleur) soit par réelles productions d'images 3D (holographie, système de restitution binoculaire de la vision du relief (type PLZT)). Des progrès sont également attendus pour l'aide à l'anticipation sur la trajectoire en évolution rapide ou en navigation très basse altitude : on citera les travaux sur la symbologie de guidage "tunnel" (à la Navy **Filarsky & Ryan, 1983,** ou en France les recherches menés sous contrôle du STTE , contrat 86.86028) en VTH ou en visualisation tête-basse.

Dans tous les cas la préparation de la mission reste une phase contribuant de façon décisive à l'évitement de désorientation spatiale ou de problèmes de perception de situations pendant le vol. Les systèmes d'aides à la préparation sont donc des aides indirectes à l'orientation spatiale et à la perception des situations. Les systèmes visualisant par simulation ce qui pourrait être la situation en fonction du plan en cours d'élaboration sont de précieuses aides quasi-opérationnelles (**NATO WG14,** Systems concepts for tactical mission planning).

4-2-2-2 Actions de formation

L'entrainement en simulateur, particulièrement l'utilisation optimale des ressources du cockpit (symbologies, modes des visualisations, entrainement au CRM(cockpit resources management)), reste un élément incontournable de la compréhension des scènes complexes. Il reste à définir quel type de simulateur (fixe, simplifié (soit dans la reproduction de la cabine, soit dans la reproduction du mouvement), complet avec mouvement) et quel type de programme (scénario de pannes... ou missions complètes) conviennent bien à ce type d'entrainement. L'état actuel de nos connaissances semblerait favoriser l'utilisation de simulateurs complets avec scénarios de missions réelles parce qu'ils sont les seuls succeptibles de présenter une réalité complexe cohérente; mais leurs coûts restent des freins à leurs développements massifs .

4-3 Aides renforcant la perception de la situation tactique

4-3-1 Actions sur les systèmes

Il n'existe pas à ce jour de système opérationnel de visualisations tactiques en unité. Aux USA, certaines versions d'avion de combat américains sont équipées à titre expérimental d'une visualisation tactique 2D, positionnée en tête moyenne, non collimatée, présentant pour un champ limité le bilan des hostiles, le potentiel agressif des ennemis, et le potentiel défensif de l'avion. Ce type de visualisation, ciblant particulièrement les conditions de combat multicibles est également en développement au niveau de la simulation chez plusieurs équipementiers Français et étrangers. Les progrès se réalisent tant sur le plan logique des systèmes et modèles des intentions des hostiles présents dans la scène que sur le plan de la présentation de l'information (introduction de 3D). Tous ces programmes de recherches appartiennent plus ou moins au domaine du copilote électronique et devraient devenir opérationnel à l'horizon 2000.

L'utilisation de l' audition ou de la stéréolocalisation acoustique constitue une autre aide complémentaire à l'appréciation de la situation tactique (positions et déplacements des hostiles). De nombreux travaux (**Naish (1989), Pellieux & al (1989), etc**) examinent cette possibilité de mieux gérer le partage de ressources intersensorielles.

4-3-2 Actions sur la formation

Il s'agit ici de l'entrainement journalier des unités de combat. On notera également l'importance à ce niveau tactique des aides à la préparation de mission, intégrant à la trajectoire les paramètres attendus de la situation tactique.

CONCLUSIONS:

La prise de conscience de la situation opérationnelle, par sa nature même, va bien au delà des classiques développements sur la désorientation spatiale. Aider le pilote pour lui éviter les désorientations spatiales ne résoud pas la compréhension de situations opérationnelles; la nature des problèmes est différente, la nature des aides est également différente (entrainements spécifiques, aides visuelles, copilote électronique).

Tout nouveau progrès requiert le développement de modèles du fonctionnement de l'opérateur intégrant l'ensemble de ces différentes notions. Il requiert également une intégration profonde des aides dans l'architecture globale d'un système d'arme, les solutions de rajout ayant toutes montrées leurs grandes limitations.

Dans tous les cas, la formation, adaptée aux différents niveaux du modèle, reste un élément clé d'une bonne perception tactique de l'environnement.

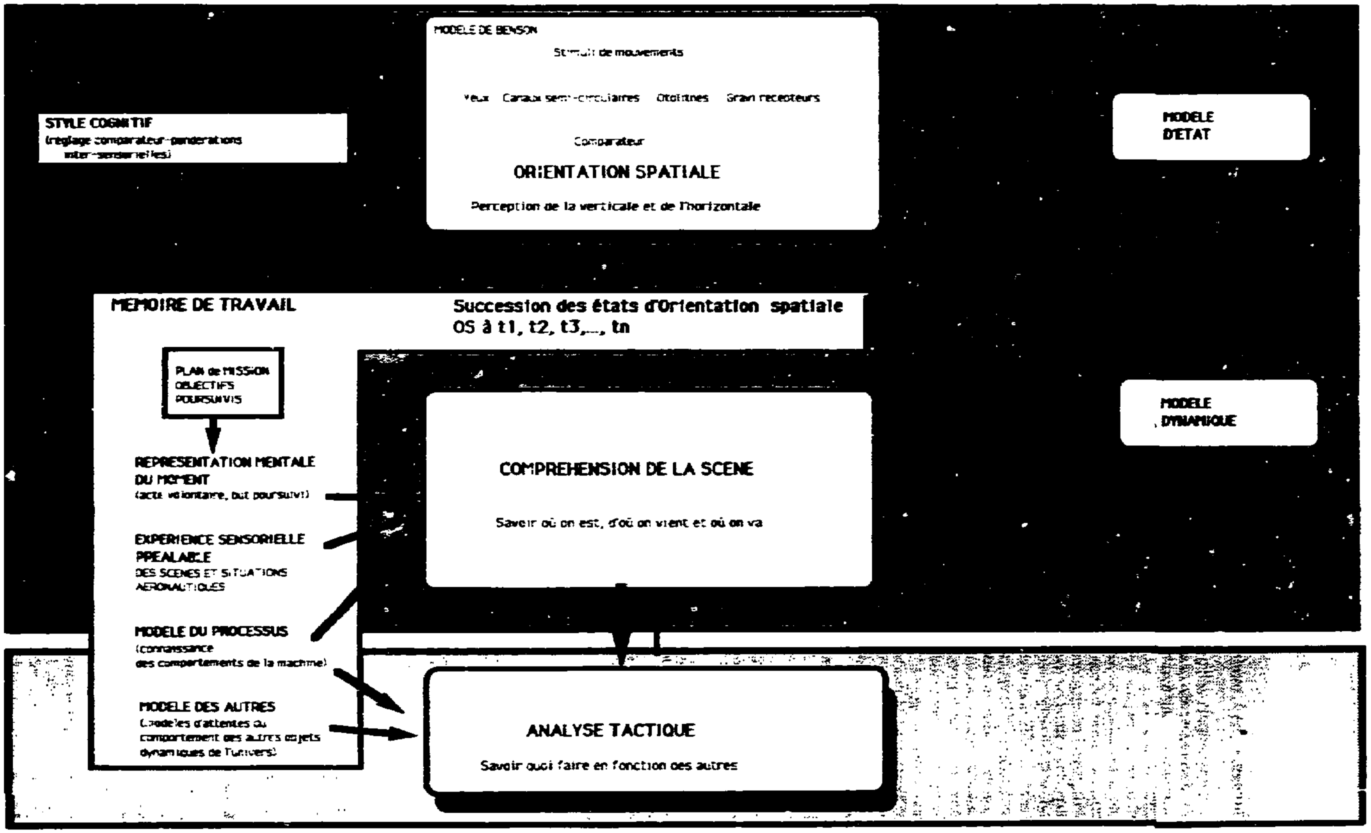

Figure 1 : Modèle heuristique de la prise en compte de la situation tactique

English Extended abstract

Les déterminants de la prise de conscience de la situation tactique et le developpement de systèmes d'aides ergonomiques

Factors involved in tactical situation awareness and the future of support systems

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1- definition(s) and model(s) of tactical situation awareness

Future combat aircrafts will have to be capable of flying anywhere, anytime and to engage air-to-air or air-to-ground attacks against a very unfavorable ratio of enemy forces. It is of clear consequence that the pilot's role will definitively turn to supervisory control and medium and long term tactical decisions whereas automatons will manage engine handling and short term activities. In this regard, and because the machines are of comparable technology in various countries, the quality of tactical situation awareness will probably largely explain the within pilots' variation of performances.

Thus, one of the most important effort for the future of combat abilities' enhancement will be to favour a good and relevant tactical situation awareness by several means including cockpit design and training. Although a very large amount of scientific papers deals with spatial orientation, very few papers deals with situation awareness and only a small part of scientific papers deals with tactical aspects of situation awareness. Everything goes as if "spatial orientation" was the scientific expression of "situation awareness" and, as if the term "tactical "was of no importance.

A mere analysis of factors involved in these concepts demonstrates all the reductionism of this position:

Spatial orientation (SO)concerns the ability to position oneself per reference to upright and horizontal directions as defined by the earth gravity. Studies in this field are of two natures: (i) local : perception and psychophysics with special emphasis on vision and vestibular interactions, (ii) global: cognitive style, namely the perception of the upright and the concept of visual field dependency. Note that much more is known on spatial disorientation (factors involved in...) than on the basic mechanisms of spatial orientation. In any case, model of spatial orientation is based on the analysis of a given state of the environment and, thus classes as a state model (as opposed to a dynamic model).

Situation awareness (SA)leads to the ability to geographically position oneself and to understand where one comes from and where one goes to. The mental model of process involved in this activity belongs to a class of dynamic models. It is partially feeded by the history of passed spatial orientations. When the process model fits the data as picked up in the environment, one say that the situation is understood. As a logical feedback, a satisfactory situation awareness considerably enhances the pilots'capabilities to analyse their spatial orientation and thus severely diminishes the occurence of spatial disorientation.

Tactical situation awareness (TSA)leads to the ability to position oneself according to relative references (friends and enemies). Once again, the mental model of expectation which has to be developed belongs to a class of dynamic models. However, the expectation model is not closely connected to the two previous items (spatial orientation and situation awareness); of course, some dependencies exist; SO and SA could be prerequisites for a powerful TSA but, because of the complete changes in references (fixed references-earth for SO and SA, not fixed references-relatives objects of the environment for TSA), TSA is not feeding back so much the SO and SA levels; these differences are of large consequence for the design of the aids and for training improvement;

In brief, the paper presents an heuristic model of tactical situation awareness with relative positions of spatial orientation , situation awareness and tactical situation awareness(table 1). The global model is considered as a two stages model : one level for SO and SA, and one for TSA.

The complete French version of the paper details the mechanisms and concepts involved in the two levels, namely vision an vestibular factors, sensory interactions, cognitive style, process model, expectation model.

The last part of the paper analyses the various ways of aiding the pilots in tactical situation awareness.

2-The future of tactical situation awareness assistance

2-1 Preliminary notes

The architecture of the previous elicited model clearly distinguishes two level of action for aids : (i)re-inforcing the earth references awareness (SO & SA) and (ii) re-inforcing the quality of the expectation model which is developed according to relative references (friend &enemies) (TSA).

-(i)because of the feedback mechanims between SA and SO, a satisfactory understanding of the scene must keep off most of spatial disorientations. Thus, maximum efforts have to be done to enhance the general understanding of the situation rather than factual assistance to spatial orientation. Exception could be observed during poorly anticipated air-to-air manoeuvers in which the assistance could focus on punctual indication of spatial orientation in order to recover as soon as possible a general understanding of the trajectory,

-(ii)tactical situation assistance cannot use the same aids as were previously defined and needs the introduction of new concepts like this of pilot's assistant. Because of the non-communality between the two levels (SO&SA / TSA), the aids have to operate in parallel and this point questions the integration of complex assistance into new cockpits which is far from being trivial (mainly because of the additional man-machine dialogue generated by the aids whereas human resources remain constant)

Anyway, assistance cannot be reduced to hardware and sofware improvements; it must be part of pilots' training.

These preliminary notes organise the plan of the paper

2-2 assistance to spatial orientation

2-2-1 hardware & software aids: the current instrument panel architecture , namely with the introduction of HUDs, allows the pilot to remain in the loop although performances are always increasing (g, speed); HUD definitively contributes to keep the pilot's gaze outside of the copckpit. HUDs enhance this combat capabilities because they favour the elaboration a better expectation model of enemies. Various solutions of hardware and software based assistance are proposed:

-the first family of solutions could consist in automatons capable of merely getting back to a safe and flat position on pilots orders. Although these automatons could save the pilot from very confuse positions, they are not good tactical tools, on the contrary!.

-enhancement of HUD is probably more efficient to preserve tactics. For many years, considerable efforts have concerned the design of symbologies in order to prevent spatial disorientation induced by HUDs (Newman, Santucci & al); special attention has been paid to the size of symbologies presented in the peripheral field of HUD (the more the excentricity, the larger the size because of the ability of the human vision-McNaughton), new symbologies have also been inserted during air-to-air manoeuvers (namely on the Rafale-plane, a mini spheric indicator has been inserted in the HUD).

Whatever the efforts, they remain limited to central vision and near central vision (the field of a current HUD is less than 30°); here is a paradox if one reminds that spatial orientation is mainly under the dependence of peripheral vision. Note also, even for central vision, the absence of a good measurement for judging the spatial organisation of visual stimuli is a large handicap . Our lab develop new concepts for such a measurement (Duval-Destin & Menu).

Because of the previously mentioned limitations of HUDs, other efforts have been paid out of the context of HUDs: at this time the best known is the Malcolm 's horizon (extension of the horizon projected in the canopy was inserted in the peripheral field of view) . Unfortunately, this tentative failed because of the inadequation to peripheral vision capabilities (too tiny line of horizon). Since this time, many studies have been conducted in order to develop specific symbologies to be inserted in periphery of the canopy; unfortunately again, up to this date, they did not succeed because of the technological difficulties to mix them with actual instrument panel 'architectures.

-as an alternative to current instrument-panels, helmet mounted display offers new solutions to facilitate data pick-up and tactical awareness whatever the direction of space which is to be monitored. But, for spatial orientation , helmet mounted display are rather worse than classic instrument panels because they include several possible gaps : horizon conflicts (the pilot is free from what he looks at but the horizon is always defined as in reference to front plane estimation), lack of cabin marks (Papin & Menu had evidenced for helicopter pilots that the canopy columns was to be re-inserted in the field of view of the helmet display in order to prevent spatial disorientation), symbologies super-impositions (between the HUD and the helmet display: some significant effort has been paid in the US to solve this problem by defining low level HUDs). Finaly, a last gap of actual helmet mounted display is monocolar technology which can generate additionnal conflicts.

2-2-2 training actions: the head down classic instrumental flying training remains of interest as a basic flying ability in spite of its being progressively replaced by new concepts of flying, namely the use of HUD and the" eye out of the canopy" concepts. Modern training actions mostly consist in the use of specific simulators (illusions siulators) in order to let the pilots experience desorientation out of the context of a task (and thus out of the possibility to use the feedback of scene understanding). The GIS located in the LEMP's lab (Mont de Marsan) is a good example of such simulator. Numerous other examples are given by similar systems in the Allied Forces.

Other complementary training can be envisaged according to the cognitive style of the pilots. It has been attempted with a satisfactory success to train people, namely students, to use a different cognitive style than they use spontaneously in order to improve their fit to situations. Some of these applications concern aerospace training but they are difficult to apply because of the lack of proficient psychologists instructors.

2-3 assistance to situation awareness

2-3-1 hardware and software aids: Hardware and sofware assistance to situation awareness could result in improving navigation displays and underlying technologies (inertial units and navigations automatons).

Current navigation automatons are now capable to operate a low-level high-speed mission according to the flightplan (e.g. Mirage 2000 N). Such systems have opened new domains of flight performances. Nevertheless, they are an additive factor to spatial disorientation because the pilot remains out of the loop; moreover, because of the logic of flight they use, they leave the pilot unaware. Strong improvements are expected with more pilot-like style of programming for the future of navigation automatons (Amalberti & al, 1987,1989).

Another way to aid the pilot in navigation and situation awareness is obviously to display an operative representation of the outside world. This representation could help the pilot as much for anticipating the automaton reactions when he flies in an automatic mode as for elaborating the future of the route and the needed tactical diversions when he flies manualy. At the time being, 2D realtime representations of the outside world become available. They could largely improve with the introduction of 3D vision either by the better use of several surface features of images (color gradation, perspectives, tunnal symbologies, etc) and/or by the introduction of holographics techniques, virtual image or PLZT goggles.

Whatever the instrument panel improvement, improvements in mission preparation are also of great interest in diminishing the occurence of spatial disorientation; namely, the mission rehearsal before flying is expected to considerably enhance pilot's situation awareness during several key phases of the mission (considerable efforts are given to this perspective , namely with the on going NATO program (Nato WG15, systems concepts for tactical mission planning).

2-3-2 Training improvements : the use of flight simulation becomes an inescapable tool for improving situation awareness. The questions are still to define (i)what kind of simulators has to be used according to their respectives advantages and disadvantages (tactical simplified simulator, fixed simulators, interactive simulators, full flight, etc) and (ii) what kind of training program has to be used : incidental situations, failures, air-to air combat, complete mission, etc. Actual training results clearly demonstrate the greater value of line oriented flight training and complete cockpit resource management (executing complete mission) rather than simulating isolated failures or isolated air-to-air combat (because a complete coherent mission provides the pilot with a strong flight context which can largely feed back and modify the local tactics as learned in very limited combat simulations or in coping with punctual failures)

2-4 tactical situation awareness assistance : At the time being, there is not existing operational tactical display. However, several versions of tactical displays are tested on flight (US AirForce) ; they take stock of the enemies and of the friends and they suggest weapon engagement.

Three D tactical displays could be operative for the next generation of combat airplan; someadvanced studies are engage for the Rafale-plane in order to operationaly define the requirements of a 3D representations of outside world: should it be displayed in the HUD (probably no), or the head level display (probably yes). Several other aspects of this 3D representation still question the scientist, namely (i) the angle and the point of view of the 3D vision (ii) the principle of image coupling according to plane motion , (iii) the level of details to be displayed, (iiii) the fidelity of data according to real world, etc. Anyway, such a 3D display will be fully compatible with additional representations as threats and tactical notes and will probably definitively enhance situation awareness.

The use of stereo-acoustic sounds to detect the enemies' position is also very promising because of the better use of human resources (Naish, Pellieux & al)

As it was for situation awareness, and whatever the technical improvements, daily operational training, namely training using realistic simulation of tactic frames,will be unescapable conditions of success.

3-Conclusion

Tactical situation awareness is far from being limited to spatial orientation. Numerous studies have been devoted to enhance spatial orientation and actual state the art confirm the significative progress done on this topic. But, as a paradox and because of the increasing capabilities of automation in handling the flight, punctual spatial disorientations of the pilot will probably be of less dramatic consequence in the future ; inversely, the key problem will be more and more to enhance the understandability of the outside world (situation awareness) in order to plan medium and long term alternatives (tactics) rather than immediate reactions. In this regard, changes in the pilot task challenge the future of tactical situation awareness assistance. Because of the new nature of problems, new aids have to be developed; the process is already on progress.

Note also that any new significant progress requires to re-envisage the whole interface in order to correctly integrate the aids. No definitive progress can be done only with corrective ergonomics.Whatever the technological progress, training must be considered as one of the key point for the enhancement of tactical situation awareness and must take into account the new tools and new concepts of training.

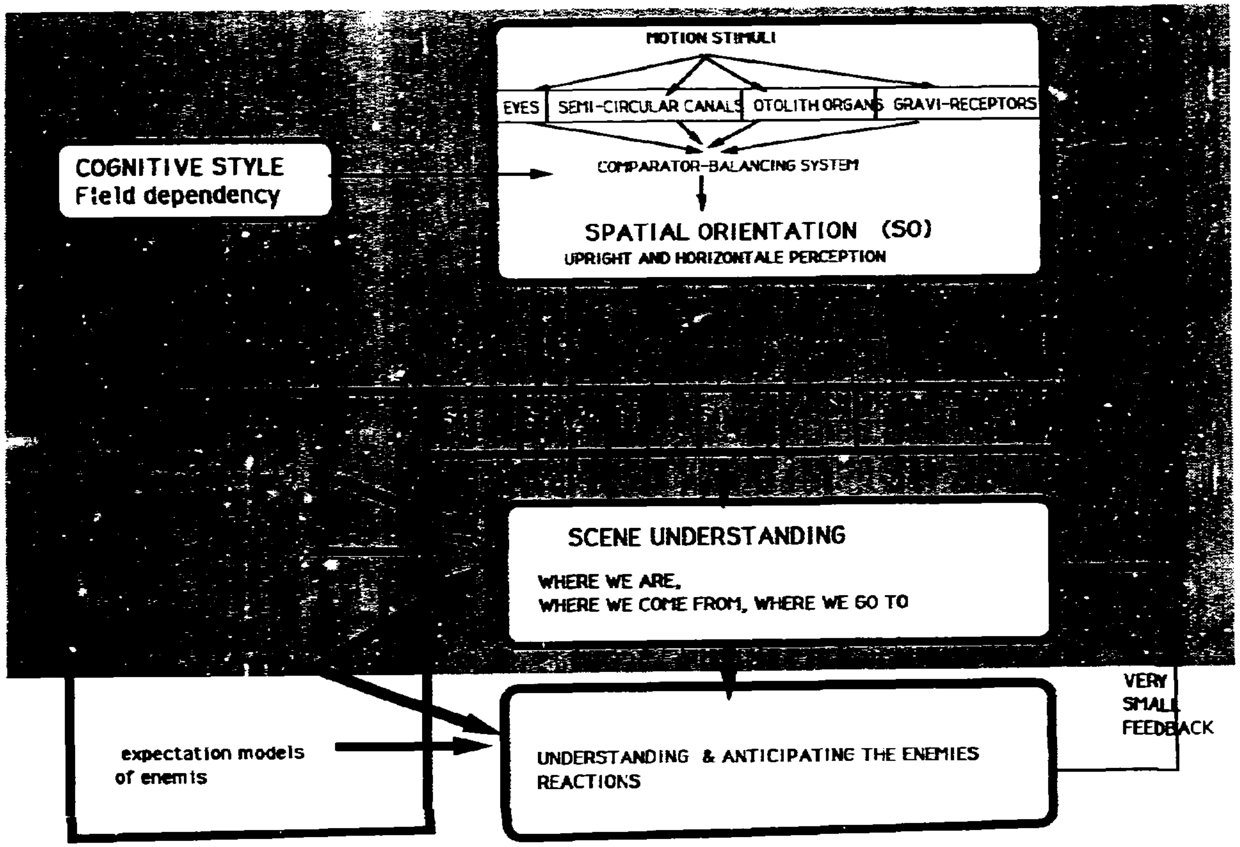

Table 1 : heuristic model of tactical situation awareness

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SPATIAL DISORIENTATION INCIDENTS IN THE R.N.L.A.F. F16 AND F5 AIRCRAFT AND SUGGESTIONS FOR PREVENTION

by

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SUMMARY

Controlled flight into terrain caused several accidents within the Royal Netherlands Airforce.
209 RNLAF fighter pilots (NF5 and F16) were interviewed to obtain information about the occurrence of spatial disorientation in flight.
Of each pilot the incident, which left the greatest impression, was analysed. 34% of those incidents is considered by the aviators as a very serious risk for flight safety.
The incidents are caused by a combination of factors, of which weather conditions, psychological factors and visual reference are the most important.
Visual and vestibular illusions are common, as well as certain psychological conditions which lead to a wrong perception of position or motion. The aspects of the sensation of disorientation are described in detail.
All pilots have experienced disorientation in some way and 26 % report that it has caused one or more narrow escapes.
73% of the pilots report a greater susceptibility for disorientation in the F16, compared with other types of aircraft.
Suggestions for prevention of disorientation accidents are given.

INTRODUCTION

Although much research has been done in the field of spatial disorientation records showed no decrease in disorientation related accidents due to that cause.
After the introduction of the F16 "Fighting Falcon" in the Royal Netherlands Airforce 18 aircraft were lost in the 10 years of operational use. Seven of those accidents were most probably due to pilot-disorientation.
In the USAF 23% of the aircraft losses and 2/3 of the fatalities is caused by disorientation, and although the F16 appears to have a very good safety record, controlled flight into terrain continues to be a big problem. (McCarthy).
The F16 has good characteristics for aircombat in clear daylight conditions, but in bad weather, at night and during high workload, some advantages become disadvantages.

METHOD

The objectives of the survey were to make an inventory of the problem and detection of the causal factors and circumstances of the incidents.
All avialable pilots, 209, were interviewed, of which 146 flew the F16 and 63 the NF5. This is a substantial and representative sample of the fighter pilot population.
The method of personal interviews was chosen because of the advantage of a better response, and the possibility of detailed questioning.
During the interviews the pilots were asked to describe their most impressive disorientation incident with as many details as they remembered. Subsequently the whole incident was analysed with a questionnaire, which consisted of detailed, categorized lists of possible causal factors. Furthermore the general incidence, susceptibility in the F16 and suggestions for prevention were subject of the interview. Anonimity was assured.

RESULTS

The age of the subjects ranged from 21 till 53 years and the experience level ranged from beginning student pilots to instructor pilots with 1200 hrs on the type aircraft.
To illustrate the problem two examples of incidents will be literally presented.

The first incident occurred to a 26 year old pilot with 580 hrs on the F16 and a grand total of 1050 hrs.
"I was flying through scattered clouds at 1200 ft during a dark night approach under Instrument Meteorological Conditions (IMC). When the plane got free of the clouds my attention was strongly attracted by an illuminated road that ran at a strange angle to the aircraft.
Because I was looking through my Head Up Display, my whole peripheral visual field was filled with this line, which acted as a false horizon.
The illusion that I was flying with much bank and pitch was so strong, that I got scared and broke off the approach. This happened a second time, before I managed to get hold of myself and could land safely."
In this incident weather, ground and cockpit design factors played a role.

The second incident happened to two pilots at the same time, one of which was a 45 year old instructor-pilot in the backseat with 4300 hrs flying time, of which 300 in the F16.
"During an intercept between two cloudlayers, we overshot the target plane. To get into an advantageous position, we made a climbing turn and entered the top layer. Because we expected to come out again any minute, we kept looking outside.
It took some time, but I didn't look at the instruments because it was all routine.
After a while I suggested to break off and set up a new intercept, and when we came clear of the clouds, under a 90° angle, we were looking at the radar to find the target.
Then I felt that something was wrong. The sky was rather dark and the white spots turned out to be wave tops. The sensation of climbing up out of the top cloud layer was soon changed for the reality of a 90° dive. We pulled 9G, to recover at an altitude of a 1000 ft."
The two cloud layers had merged and because of the somatogravic illusion, they didn't feel that their climbing turn had become a coordinated loop.

All the incidents can be categorized as type II disorientation, the recognized type.
Type I, the unrecognized type and, often fatal, cause of controlled flight into terrain, cannot be investigated by means of an interview. Fortunately, many of the type I disorientation changed in time in type II to avoid an accident.

Circumstances and causal factors

The most impressive incidents were analysed in detail. The categories of factors that contributed the most to the problem were weather conditions, psychological factors and the visual references (fig.1). In many incidents, it was a combination of factors, that made it possible for the disorientation to evolve.

Factors like cockpit layout and airplane characteristics scored substantially higher in the F16 incidents than in the NF5 incidents.

The flying experience of the aviator played only a minor role in most cases. Pilots of all ages and all experience levels experienced disorientation. In those incidents, where experience played a role, some younger, unexperienced pilots had difficulties with the vast amount of possibilities in the plane or didn't know its limits very well. This caused distraction and high workload. However, some experienced pilots had overconfidence.
Student pilots as well as flight leaders, commanders and instructor pilots got disorientated.
Most pilots had an operational status. Those who flew after a long period of non-flying sometimes encountered trouble. This occurred also during the first night flying trip after a summer period.

The function during the mission played a role when it was a "close formation" situation. Especially student pilots, who often fly as wingman, had problems with the "leans". A climb out, with the radar locked on the leader, was a reason for overconcentration on the radar screen in a few cases. The absent instrument crosscheck prevented detecting a descending flightpath, while pitchup was felt because of the somatogravic illusion.

Last minute changes in the planning and "hot scrambles" caused high workload and wrong priority setting in some cases and gave disorientation a chance. And unclear preflight briefings brought pilots in unexpected situations, which led to extra workload.

The day of the week an time of day played no clear role in causing the disorientation.

Flighttime was slightly more important. Fatigue after a long flight or rapid changes right after take off contributed to the disorientation.

65% of the incidents occurred under 1Gz conditions. In those incidents were Gz played a role, high G-forces or negative Gz were involved and caused distraction or vestibular illusions.

In 83% of the F16 incidents and 63% of the NF5 incidents visual reference played an important role.
Especially looking through the Head Up Display (HUD),wich 22% of the F16 pilots did at the moment of the incident, caused disorientation. This due to the poor horizon indication, the rapid changing digital numbers and the peripheral visual influence. Overconcentration on the radar was also a reason for paying less attention to the primary flight instruments (PFI).
39% of the NF5 pilots and 47% of the F16 pilots mentioned, that the fact they were looking outside for sometime, was a major cause for the disorientation incident. This occurred in close range aircombat, during flying "on the wing" and while staying visual in the clouds or without a well defined horizon.
Constant diversion of attention to the outside world, radio, HUD, radar and the PFI also evoked disorientation (fig. 2).

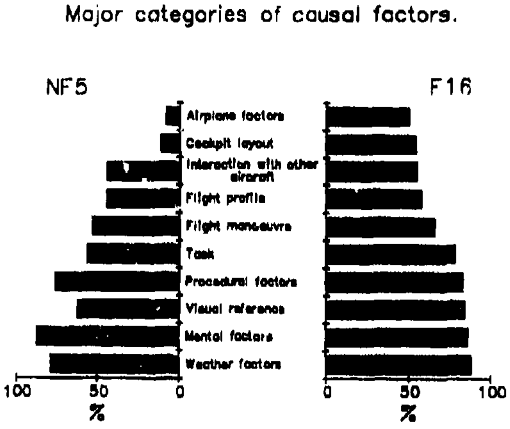

FIG.1

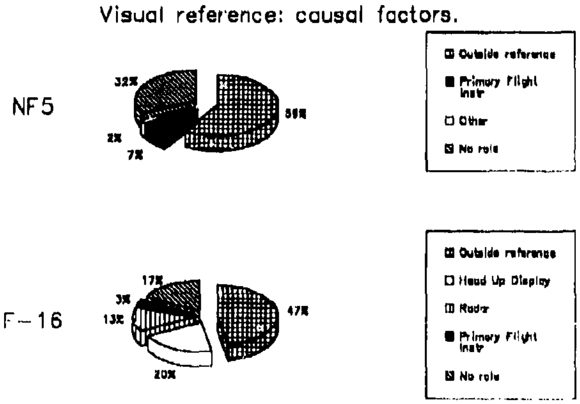

FIG.2

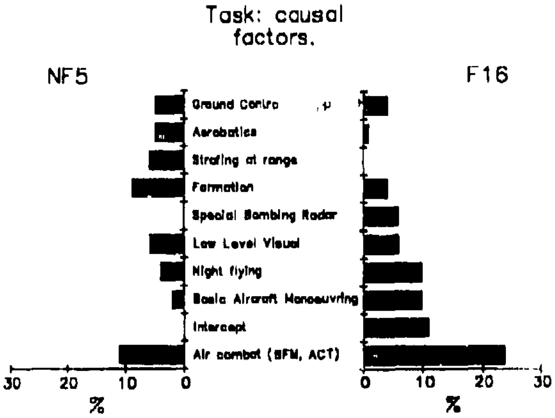

FIG.3

The task was of great importance in causing disorientation. Especially aircombat was a factor (24% F16, 11% NF5). Eagerness to win led to fixation on the targetplane and a wrong priority setting. The rapid Gz-onset and overload because of inexperience were often reasons for this significance.
Aerobatic aircraft manoeuvres during bombingtrips made the pilots susceptible for vestibular illusions.

Night missions were dangerous, because of the confusing lights, that gave visual illusions.
Formation flying often caused the "leans", while weapon exercises sometimes led to target fixation (fig. 3).

The flown profile was of importance, when the pilot had to make many manoeuvres and had no time for a crosscheck, while he was influenced by confusing vestibular input. Turning the head during such profiles aggravated the problems.

The manoeuvre at the moment of disorientation was also mentioned as contributing factor. Climbing caused "pressure vertigo" and the take off with after burner caused pitch up sensations. Long turns or subthreshold turns were cause of many sensations also, like the "leans" and the sensation of climbing in a turn (fig. 4).

70% of the F16 and 84% of the NF5 incidents occurred during day time. 57% and 70% respectively occurred under visual meteorological conditions (VMC).
The weather conditions formed the most important group of causal factors. Weather conditions were involved in 79% of the NF5 incidents and 88% of the F16 incidents it played a role. Especially flying under Instrumental Meteorological Conditions (IMC) was disorientating.
Sudden entry in IMC caused a "lost horizon" sensation and was confusing, as well as flying through scattered clouds. The pilot can also loose his correct idea of the horizon when flying in a "fish bowl", caused by cirrus clouds that give a total white surrounding with an otherwise good view.
Night flying sometimes caused star-groundlight conflicts or "black hole" approaches. A hazy layer or a grey mix of low clouds and sea surface deprived the pilot of a horizon also and gave way to illusions (fig. 5).

The various groundfactors that played a role in causing visual illusions (F16 34%, NF5 32%) were flying over open sea, which caused a false perception of height, flying over a dark terrain with few ground lights, which caused a star-groundlight conflict and illuminated roads or dikes, which gave false horizons. Climbing terrain was mentioned as an important groundfactor also. It was detected late in some cases.

Problems caused by interaction with other airplanes (F16 55%, NF5 45%) occurred especially during aircombat ("loss of situational awareness") and flying on the wing ("leans"). Warnings from the ground; or other aircrafts radar during intercepts, caused problems because of distraction and coning of attention (fig. 6).

The aircraft itself was the source of several disorientating factors. In 50% of the F16 incidents this played a role, compared with 9% of the NF5 incidents.
Lack of speed sensation, rapid acceleration and high manoeuvrebility were the most important factors. The moving landing lights can be disorientating when the landing gear comes down. They reflect on the clouds during a night approach (fig.7).
In the NF5 it was mostly aircraft malfunctions that were disturbing.

Another difference between F16 and NF5 was found in the role the cockpit layout played, 54% to 12%. The high sitting position of the pilot, the frameless bubble canopy, the low canopy edge, lack of airplane reference and a large peripheral visual field were the causal factors.
Moving, colourful reflections of the instrument lights, or of bright sunlight, in the canopy caused the "Star Wars" effect, which induced distraction, irritation and vection illusions, as well as a diminished visibility. The instrument location and the small F16 instruments were also factors that played a role.
Characteristics of the Head Up Display played a role in causing a disorientation incident. The small size and the interpretation of the digital speed and altitude indication ladders were a problem, as was the horizon indication (fig. 8).

Physical factors involved were: Head movements in turns, which caused G-excess and Coriolis effects. "Grey outs", because of high Gz-turns. Rhinitis, that led to pressure vertigo. Illness because of fatigue or alcohol. These factors played a role in 29% of the F16 incidents and 27% of the NF5 incidents.

Psychological factors played a substantial role (F16 86%, NF5 88%).
Overconfidence was a factor, both before and inflight. During flight common factors were: lack of vigilance and risk awareness, early relaxation after a target and a false sensation of safety, the "flying carpet" fenomenon. A high workload did lead to channelized attention, distraction, preoccupation with one task and tasksaturation. This gave illusions a chance. Target hypnosis occured more in young pilots because they wanted to perform optimal (fig. 9).

Systemfactors were less important (F16 27%, NF5 15%). Changing frequences during stressfull periods and busy radio communication led to distraction.

Flight rules played a role in 84% of the F16 incidents and 76% of the NF5 incident.
The main factor that was indicated to cause the incident was the lack of instrument crosscheck. Incomplete crosschecks and maintaining VFR under IMC were also a problem. And there were several pilots who disregarded procedures or broke rules. Poor lookout and headmovements during turns were also mentioned (fig. 10).

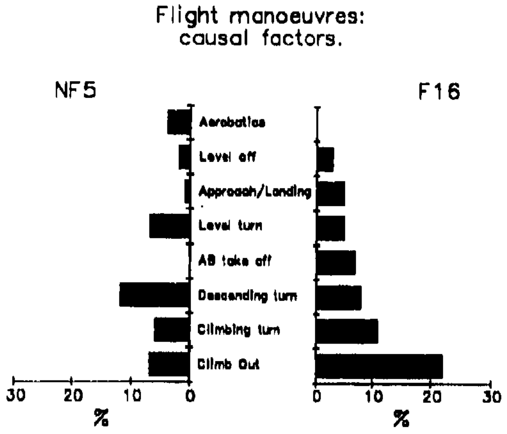

FIG.4

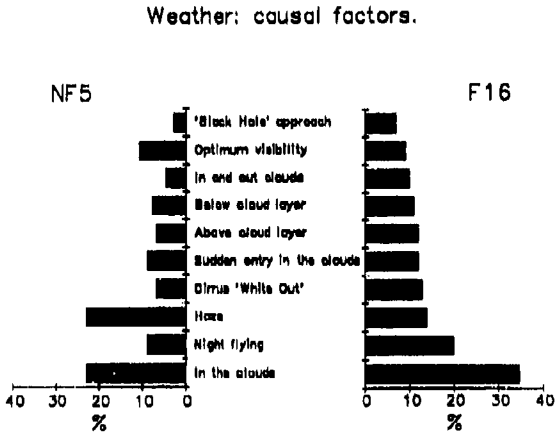

FIG.5

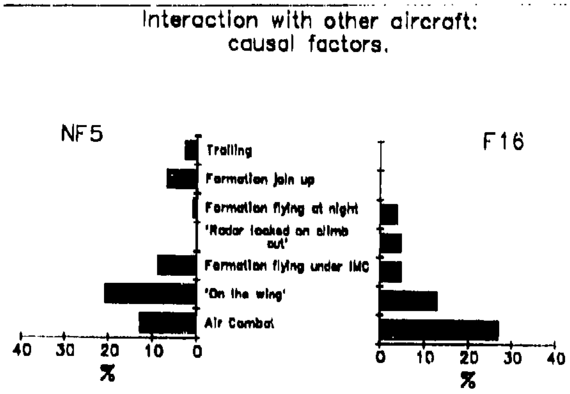

FIG.6

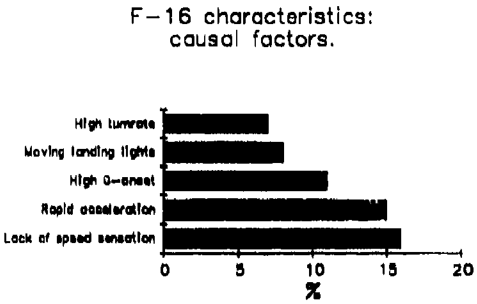
F-16 characteristics: causal factors.

FIG.7

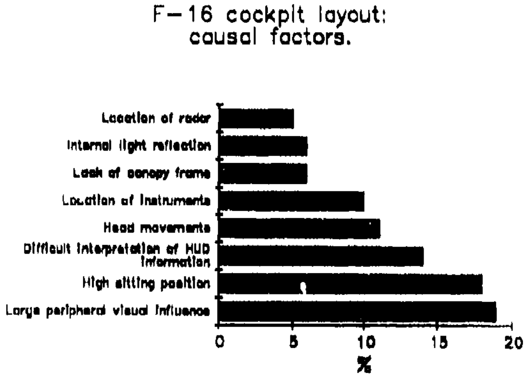
F-16 cockpit layout: causal factors.

FIG.8

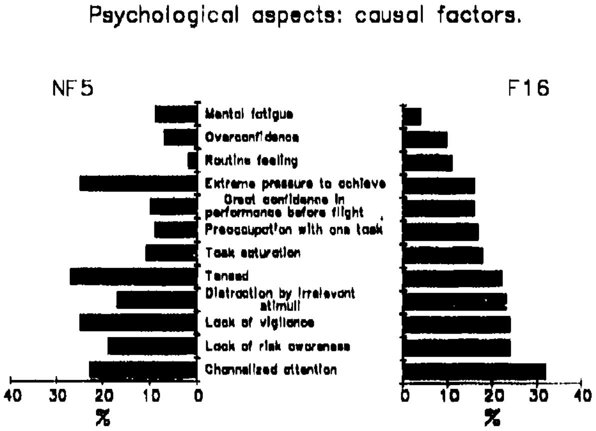
Psychological aspects: causal factors.

FIG.9

Of all the specific causes the most important was the fact, that the aviators had no attention for the instruments. Other closely related factors were looking our for too long, flying under IMC, and having too much attention for the target plane during aircombat. A complete, frequent and conscious crosscheck is missing in many cases. (fig. 11).
In many cases a complete, frequent and consious crosscheck is lacking.

Illusions

The sensations experienced by the aviators are categorized in 5 groups:
Visual illusions : A. focal vision
B. peripheral vision

Vestibular illusions : C. semicircular ducts
D. otolith organs

Other phenomena : E. mental states

In the latter case there was no clear sensory illusion, but a lack of mental control over the whole situation which gave the pilot a false idea of the correct position. Often several illusions occured at the same time, illustrated by the incident of a pilot during air refueling at night: The constant turn gave him the "leans", all the lights caused a star-ground light conflict, the anti collisionlights caused "flicker vertigo" and a closely overflying airliner, with illuminated windows, attracted him so much that a vection illusion resulted (fig. 12 and 13).

The most common illusions of the focal vision were a false perception of height, absense of adequate visual stimuli and the star-groundlight conflict.
Low level flying over smooth water surfaces, deserts, snow covered landscapes or climbing terrain were major causal factors for a false perception of height. This occurred to 6% of the F16 and 9% of the NF5 pilots. In combination with distraction this led to near disasters.
An example of absense of adequate visual stimuli (6 and 2%) is the aviator who was topping fleecy clouds at night and discovered only just in time that the next cloud was a snowcovered hill top. Loss of detail causes wrong interpretation of distance, shape and speed.
The star-groundlight conflict in 5% of the F16 incidents, was caused by flying visual over a dark terrain or sea with some light spots. The real horizon was sometimes hard to find.

The difference in peripheral visual illusions between F16 (37%) and NF5 (20%) might be due to the high sitting position of the F16 aviator under the frameless bubble canopy.
The "lost horizon" (13 and 4%) was often the result of sudden entry in the clouds while the pilot flew visual or was busy with demanding mission requirements. The total loss of any horizon reference can be very confusing and gives also rise to vestibular illusions. This also occurs in dark nights ("black hole" approaches), after lightning strikes and at very high altitude.
The "false horizon" (7 and 3%) was often caused by illuminated roads or dikes, sloping clouddecks and the wings of the leader, during close formation flying in the clouds.
Vection illusions (8 and 2%), rotating as well as linear, were the result of rotating anti collision lights or landing lights reflecting on the clouds, stroboscopic runway lights or relative motion of other aircraft.
The reflection of instrument lights caused a severe "Star Wars" effect of moving, colourful stripes in rare cases. Some of the pilots experienced the "lean on the sun illusion" when flying in the clouds with the sun shining vaguely through the clouds.

Although the 2 vestibular systems, semicirculair ducts and otoliths, are closely related, some of the illusions are clearly caused by information derived mainly from one to the two.
37% of the illusions in the F16 and 29% of those in the NF5 originated in the otolith organs.
The high acceleration in the F16, during take off with afterburner, caused somatogravic illusions in 10% of the cases (NF5 3%). At night or under IMC this occurred more often. Attention for other instruments than the attitude indicator, like radar, led to pitch input as a reaction to the illusion.
The sensation of climbing in a turn was a clear illusion in 13% of the cases in both groups. Especially in situations without horizon reference, it led to false input.
Headmovements during turns, such as a switch from Head Up Display to radar, was the cause of the G-excess effect. This led to false sensations of attitude (1 and 3%).

The classic illusions originating in the semicircular ducts were as common as expected (F16 39%, NF5 41%).
A false sensation of bank was experienced by 12% of the F16 and NF5 pilots. They started a subthreshhold turn without knowing. Especially under a high workload during low level flying, or because of distraction under IMC, this type I disorientation almost caused accidents. Only by crosschecking the instruments in time or seeing the ground coming up, a collision could be prevented.
A distinction is made between a false sensation of bank and the "leans". In those cases, 5% of the F16 and 21% of the NF5 illusions, the pilots knew from the start, that what they felt did not fit the instrument information. They were struggling against their known wrong feelings while flying in close formation. The sensation was very strong and lasting in some cases and caused dangerous situations during approaches and landings. Student jet pilots fly the NF5 at the beginning of their career and a great deal of that time is spent "on the wing". This explain [illegible] great difference in occurence.

Flight rules: causal factors.

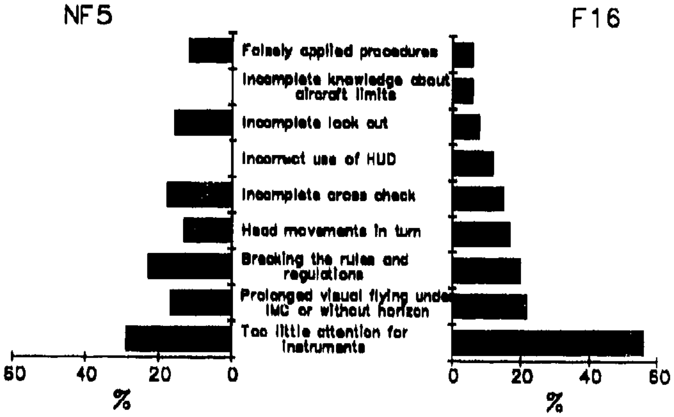

FIG.10

Most frequent causes.

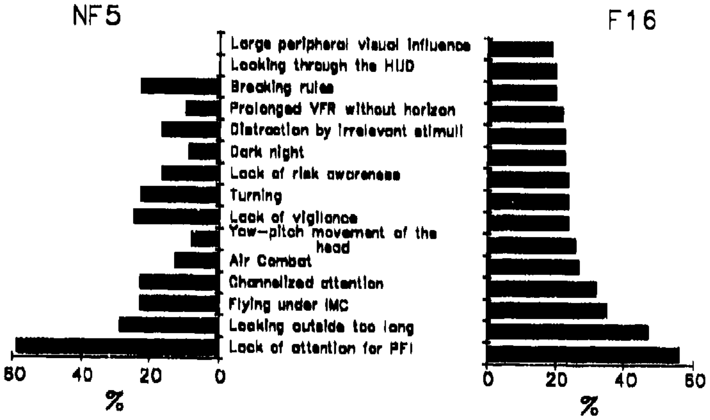

FIG.11

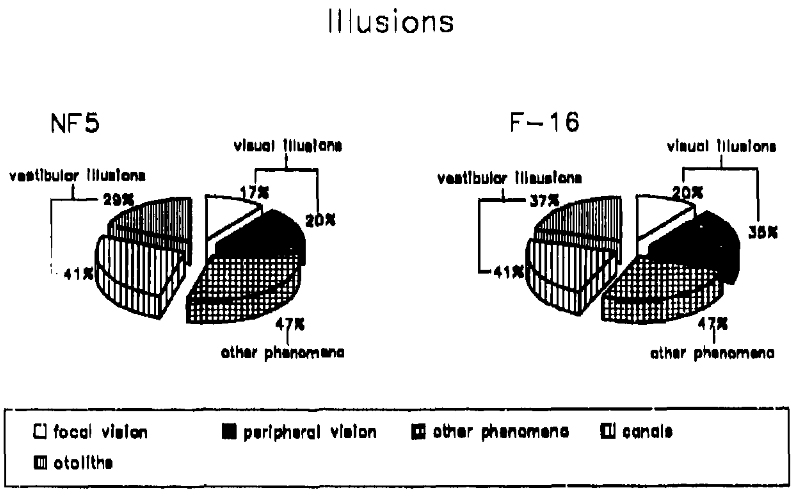
Illusions
NF5
visual illusions
vestibular illusions
29%
17%
20%
41%
47%
other phenomena
F-16
visual illusions
vestibular illusions
37%
20%
35%
41%
47%
other phenomena
☐ focal vision
■ peripheral vision
▦ other phenomena
▥ canals
▥ otoliths

FIG.12

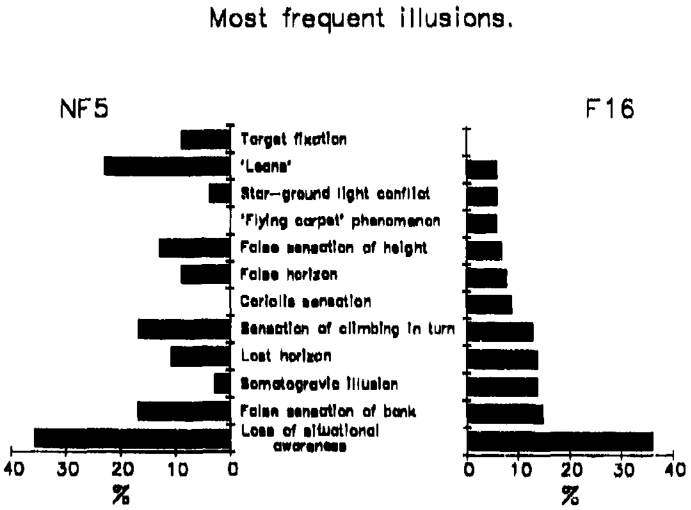
Most frequent illusions.
NF5
F16
Target fixation
'Leans'
Star–ground light conflict
'Flying carpet' phenomenon
False sensation of height
False horizon
Coriolis sensation
Sensation of climbing in turn
Lost horizon
Somatogravic illusion
False sensation of bank
Loss of situational awareness
40
30
20
10
0
%
0
10
20
30
40
%

FIG.13

Sensations caused by turning the head during aircombat, without visual reference, occurred in 4% of the F16 and 1% of the NF5 cases. These sensations were very confusing and contributed to a loss of situational awareness. The Coriolis sensations are probably for a great deal due to the G-excess effect (Gillingham).
Furthermore there were some cases of somatogyral illusions, due to "pressure vertigo", caused by flying while suffering from a cold.

In 47% of the incidents there were no evident sensory illusions which caused the disorientation. In those cases a psychological state of mind was involved, that gave the pilot an incomplete idea of his position. The most common sensation of this category was the "loss of situational awareness", 29% of the F16 pilots and 27% of the NF5 pilots experienced this in a severe way.
In those cases the pilot was so busy with aircombat that he lost the overview of the situation. He knew where the target was, but realised, that he did not know his own position or where the ground was or where the other planes were. This explanation is assumed in more and more accidents. The present generation fighter planes are very advanced and give the pilot more, instead of less, workload. They also allow a short range, high Gz, dogfight, in which there is hardly time for a good crosscheck. Because of overload, the aviator looses the total picture of his position. But in the NF5 also it was a frequent illusion. When he is not aware of it, the pilot can collide with the ground in the middle of aircombat (type I). Visual and vestibular illusions can contribute to the problem.
A typical F16 sensation is the "flying carpet" effect (4%). Sitting high and comfortable on top of "the best airplane in the world" some pilots got a false sensation of safety andthe feeling that nothing could happen to them. They just cruised into bad weather with little vigilance or came much too low without seeing the danger.
Other phenomena were "flicker vertigo", irritating sensations because of anticollision lights reflecting on the clouds, and target fixation, especially in NF5 incidents (7%) because of the new, frequent weapon exercises of student pilots, who were eager to score.

Analysis of the disorientation sensation

The quality of the sensation and the effects differ between the incidents.
The detection of the fact that the pilot was disorientated was in most cases "a matter of instinct". In 70% of the F16 and 43% of the NF5 disorientation cases the aviator just "felt" that there was "something wrong". They felt uncomfortable, because they noticed that they lost position awareness or missed visual grip on the outside world. This led to checking the instruments or visual verification of the distance to the ground. A much smaller percentage (F16 21%, NF5 11%) noticed disorientation for the first time, while checking the attitude indicator. The altimeter was usefull in 19% of the NF5 cases, compared with 7% in the F16 incidents.
Sometimes different cues together led to the detection.
The difference in percentages (instinctive detection, altimeter) is probably caused by the cockpit layout and the higher sitting position in the F16. Other ways to detect the problem were audiowarnings, crewmember or ground warnings, aircraft behaviour, sudden awareness of the distance to the ground and the attitude indication in the Head Up Display. This last one only helped in 2% of the F16 cases because of the difficult interpretation of the HUD information.
Although it is hard to say how long one was unknowingly disorientated most illusions were detected in 2 to 10 seconds.

The subjective strength of the sensation varied. In 50% of the incidents the aviator said it was a strong sensation. Around 20% could not get rid of the sensation untill the causal factors, such as lack of visual reference, disappeared. Using the instruments solely was not enough.

The realization of being disorientated had some important psychological effects.
Most of the pilots (NF5 44%, F16 56%) acted according to the instruments although they were amazed, confused, or shocked.
More dangerous effects were reflex actions, 25% of the NF5 and 18% of the F16 pilots reacted to the feelings before evaluating them, for example pitch down input after somatogravic illusions or pitch up during take off. The "giant hand" phenomenon was mentioned as well. A small group did not believe the instrument information for a while, were fixated on one instrument only or even sat "frozen at the controls".

Control of the aircraft was lost in 6% of the F16 and 3% of the NF5 cases. In about 50% of the incidents the aviators kept full control over the airplane, in the remaining cases control was decreased or the autopilot or crewmember flew the plane.

The solution of the problem was mainly done with information of the main instruments. 47% of the NF5 and 59% of the F16 pilots could recover from the sensation that way. Manoeuvring the airplane often helped to get the correct idea of position again.
Outside reference was also important. For 51% of the NF5 pilots and 29% of the F16 pilots, it was enough to see the ground coming up fast to forget the idea that the aircraft was in straight and level flight. In some cases, like the "leans", it took up to 20 minutes before the pilot felt allright again, but most sensations lasted from a couple of seconds to 2 minutes.

When the plane came on an undesired flight path because of disorientation guided input, it had to be corrected. Most of the pilots did this, by using instruments (45%), or by using the outside reference (NF5 44%, F16 20%).
The Head Up Display played only a minor role in ending the sensation or correcting the flight path.

All interviewed aviators remained unharmed, although the aircraft sometimes was damaged during these most impressive incidents by hitting treetops or making hard landings.
About 33% of the pilots interviewed categorized their incident as a major risk for flight safety. 10-15% saw no risk in the situation.

Overall incidence

Apart from the most impressive or most dangerous incidents, the pilots were asked about the general incidence of disorientation. All pilots had experienced some kind of disorientation during their career. In most cases this involved "the leans", beside some visual illusions.
Of the F16 aviators, 26% had a near accident during his flying career and 8% mentioned to have this once a year. In the NF5 population these numbers were 18% and 5%.
These are subjective numbers; an objective observer could have had another opinion.
"Loss of situational awareness" was most often involved in these situations (12% F16, 5% NF5). This was caused by a high workload during aircombat.
Other causes of near accidents were the false perception of height (5% F16, 3% NF5), false sensation of bank and the "flying carpet" phenomenon.Target fixation scored especially in the NF5 population (3%). Distraction and high workload were important factors.
Disturbing sensations, that were not dangerous (F16 60%, NF5 31%), were in most cases also "loss of situational awareness", but the "leans", "lost horizon", somatogravic illusions, false horizon and G-excess or Coriolos illusions occurred frequently also.
And all pilots regulary encounter minor illusions in the form of fast detected and solved "leans", star-groundlight conflicts, "false horizons", etc.

Disorientation and the F16

Susceptibility for disorientation in the F16.

The 146 F16 aviators were asked if they experienced more disorientation while flying in the F16 as compared with other planes, such as F104, NF5 and other types.
25% mentioned it was identical. A group of 73% experienced more disorientation in the F16, of them 48% had somewhat more problems and 25% had far more disorientation sensations. In some cases the aircraft was appreciated as less disorientating.

The circumstances in which the F16 pilots were more subdued to illusions, involved mainly flying under IMC (51%), at night (35%), in aircombat (30%) and during formation flying (10%).

The reasons for greater susceptibility were diverse.

F16 flight characteristics were a very important factor. Because of the aerodynamics of the plane there is no sensation of speed. The pilot feels or hears no difference between 200 or 600 knots. Especially in aircombat this causes problems.
The "fly by wire" system, in which the computer does the actual steering, causes a lack of feedback from the stick. There are no forces from the stick that let the pilot know what the aircraft is doing. The correct sensation of attitude is more difficult to get that way.
Because of the high manoeuvrability, the sharp turns with high G-onset, the pilot experiences more disorientation. The workload is high and because of the possible tasksaturation this can lead to channelized attention and lack of a good instrument crosscheck, which can result in "loss of situational awareness".
The linear acceleration during afterburner take off caused somatogravic illusions. The fact that the plane is easy to fly in a comfortable position led to the "flying carpet" sensation in some cases.

There are some aspects about the position of the pilot in the aeroplane that lead to more disorientation in a number of pilots. The lower edge of the cockpit is near to pilots upperlegs and he is sitting under a bubble canopy with a 360° field of vision and no frame for airplane reference.
Because of this high sitting position there is a large influence from the peripheral view, for example when he is looking through the HUD. The aviator has little or no possibility to escape from internal or external light reflections.
Sitting high on top of the aircraft, that can hardly be seen, also contributes to the "flying carpet" phenomenon.

The Head Up Display (HUD) is a sophisticated instrument that creates several problems. The 37° angle between HUD and the radar screen necessitates pitch movements of the head, which can create G-excess illusions in turns. Also the distance to the other instruments is too large. Interpretation of the digital speed and altitude indication is very difficult in periods of stress. There is hardly any difference noticable between rapid changing numbers, 1.000 ft can be interpreted as 10.000 ft. Horizon and up/down indication is another problem. During approach this creates problems. In the dogfight mode there is no horizon indication at all, and in these situations, that lead to loss of situational awareness quickly, the pilot primarily needs just that. Especially when there is no well defined horizon. The present HUD is too small (10 by 10 cm), so the pilot has to make movements around to see all information, and the motion of the projection itself is disturbing.

The cockpit layout is a disorientating factor because the primary instruments, like the attitude indicator, are too small, too far away and placed too low. Developed as a daylight fighter, the main instruments were less important than the view. In the European Theatre with its bad weather however, the pilot needs a quick and easy crosscheck possibility. Certain instruments he needs in stressful periods are placed at distracting locations and make headmovements necessary. The modern avionics and the vast number of possibilities raise the workload.

Another disorientating factor, that is connected with flying the F16, is the possibility of climbing out after the leader while locking him with the radar. This can cause channelized attention on the radarscreen and reactions on somatogravic illusions.

The moving reflections of landinglights on the clouds, when the gear comes down during an approach in the clouds at night, can cause vection illusions.

The operational use of the F16 also plays a role because of the high workload during demanding missions in bad weather.

Suggestions for prevention

The causes, illusions, incidence and F16 susceptibility give a picture of the disorientation problem within the Royal Netherlands Airforce. To prevent any future incidents and accidents many changes and improvements are needed. The interviewed pilots were asked for suggestions to solve the problem and made the following recommendations:

Frequent briefings on the subject are very important. From flight commander and flight safety officer to medical corps, all levels should regulary brief on the importance of a good, regular crosscheck and the dangers of flying. Before special exercises, like low level flying over the desert or over snow covered areas attention should be drawn to specific problems. Student pilots that go on their first special mission should be briefed on the dangers of that mission. Accident investigation reports should come to the squadrons quickly, otherwise the preventive effect will be lost. A preliminary report, within two weeks, is important. Realistic recordings of accidents, will have an important impact. Daily debriefing of all incidents, and a possibility to anonymously report an incident will provide colleagues with useful information.

With demonstrations the effect of high workload on the crosscheck and the effect of disorientation on performance can be shown convincingly. Inflight demonstrations are very useful, because the sensations are real and the psychological effects will have a great impact. These demonstrations, however, cannot show everything, moreover, they are not without danger.

Ground based devices are more practical and can show more illusions, but have to be very realistic to convince the aviator. They should be equipped with a very good visual system, a realistic cockpit layout, feedback possibility, motion in 3 axes and some amount of G-forces to be real enough. Also the pilot has to fly a "real" mission with a high workload and distracting features. Only than the necessity of a good and regular crosscheck can be demonstrated.

Some disorientation demonstration can be done in an operational flight trainer or in an aircombat simulator, to show visual illusions or the development of the "loss of situational awareness".

Instrument flight (IF) training should be practised often and thoroughly, so the pilot will not be in a new situation when he enters bad weather, which is one of the most important factors causing disorientation. This must be done in the simulator, but inflight also. More IF training hours are needed and there should be regular IF checks by instructors.

To practise instrument flying in good weather, there should be possibility to cover the cockpit or otherwise prevent outside reference. "All weather" strike missions can be exercised then.

The pilots must learn how to fly an approach without use of the HUD. And when the plane gets into an unusual attitude, the aviator has to know very well how to recover in time. This too should be trained more often, so the pilot knows what to expect.

The organisation itself needs to be changed also on several points, according to the aviators.

The F16 is a demanding aeroplane that has to be flown regulary to stay proficient. It takes quite some time to get fully acquinted with the plane and especially student pilots need many flying hours a week to learn how to fly the plane safely and efficiently.

The NATO standard of 240 hours a year should be flown, with a minimum of 90 hours for staff pilots.

The technical knowledge of the pilots about the F16 is jeopardized by mandatory attention to other activities like exercises, meetings, courses.

More wartime task training is necessary to know how the plane will react to a full bombload, for example.

The lack of experienced pilots is a big problem. Many of them left the airforce for better paid or "healthier" jobs, or they were transferred to a "paper" job at the airforce staff. The consequence is less instruction. Young pilots are being pushed to fly difficult missions without proper experience or to take responsibilities beyond their capabilities. Measures should be taken to keep experienced pilots in the airforce and in the field of flightinstruction. More demanding functions should only be given to the aviators who meet the requirements.

Supervision remains important, to prevent young pilots going too far to impress their collegues and to prevent overstressed or unfit pilots going on a demanding mission. There also should be regular flight safety checks. The importance of regulations and procedures has to be often repeated.

To prevent high workload during the flight, the planning must be optimal, including the last part of the mission, after the target is made.

One of the operational suggestions that have been made, is more use of the autopilot. Using this feature in "altitude hold" during instrument flying over flat terrain decreases the workload.

After a period of non-flying a G-warmup is necessary. After aircombat it is not advisible to enter the clouds in close formation, to prevent the "leans".

Young student pilots should go on their first difficult trip with an instructor.

A "radar locked on behind" climb out with several aircraft has to be avoided especially for unexperienced pilots.

Every demanding or distracting action to be taken during low level flying should be preceded by climbing. All attention has to be on the flying and when there is not much detail visible the pilot should not go very low.

To prevent reflections in the canopy, non-reflecting materials should be used.The HUD should not be used during extreme manoeuvres or during bad weather. If there is any problem the pilot should transfer to primary flight instruments (PFI) and remain there.

If the pilot comes to the conclusion that he is disorientated he must terminate the manoeuvre, level off, use only PFI, keep his head still, switch on the autopilot in altitude hold and put all instruments correct again.

The F16 cockpit layout causes a greater susceptibility for disorientation.

Several structural changes are needed. A lower illumination level of the instruments and radar and non reflecting materials can prevent the "Star Wars" effect.

The basic instruments should be placed right in front of the aviator in the right order for a good, quick crosscheck.

"Heads up and hands on" decreases distraction and headmovements.

The instruments should be larger and more reliable, e.g. the standby attitude indicator.

All equipment to be used in combat situations should be forward, like the fire control navigation panel and the switches for chaff, flare and electronic counter measures, as well as the video switch. The last item can possibly be connected to the "dogfight override" switch.

The Head Up Display is going to be replaced by a wide angle version (15 by 15 cm). This must give the pilots a better view of all information. A better up/down indication, instead of the present dotted lines should be presented as well as a good horizon in the dogfight mode.

A good "off"-indication is necessary. To warn the pilot that the HUD has a malfunction.

Round dials are perhaps better interpreted in stressfull periods with rapid changing speed and altitude.

The present HUD is not yet fit to be used as a primary instrument because of the mentioned short comings and it is not to be used in stressful periods or to solve disorientation.

Many technical improvements have to be made.

A combined altitude radar altimeter (CARA) will give the pilot more chance to avoid a collision with the ground. An automatic low altitude warning with audiosignal has to be built in, and this may prevent a number of accidents.

A moving map display will help the pilot to create the correct picture of where he is going. This lowers the workload. The abstract waypoints, like they are shown now, are not convincing enough. Looking on a map during low level turns creates dangerous situations.

Perhaps a transparant frame can be fixed on the canopy, to have an aircraft reference. Visual illusions during approach can be partly compensated for by a visual approach slope indicator system (VASIS) on all airfields.

It is possible that some of the missions flown in the F16, such as "all weather" strike, are too demanding for one person. Dual F16's may be needed in those cases, untill better hard and software can take some of the workload away from the pilot.

Certain techniques which are being tested may prevent part of the disorientation accidents.

The Data Transfer Unit (DTU) will reduce workload during flight preparation.

The terrain following radar, which is in use in several types of aircraft, is necessary for safe low level flight in mountainous terrain, at night, or in bad weather. The negative side is the tracing problem. A terrain reference system is passive and will tell the pilot where the ground is or where obstacles are at all times and warn him in every possible way, while the aviator pilots the plane himself, with or without night vision goggles.

A ground avoidance system can take over if an ultimate 9 Gz pull up is needed to avoid a collision. Other navigation systems, are the global positioning system and "fusion" systems,in wich radar and infrared information is combined with the map display. A combination of these systems may reduce the workload and will be an improvement for flight safety.

Developments like the Malcolm horizon, direct voice control, touch sensitive screens and helm mounted displays if fail safe and used in the right way can make flying in high performance aircraft even safer.

CONCLUSIONS

All interviewed aviators have been disorientated in some way during their career. It occurs at all ages, on all experience levels and in all aircraft and it is often a combination of factors that causes the problem. Most important are weather factors, visual reference, psychological and procedural factors.

All these factors lead to a poor instrument crosscheck. This makes it possible for visual, and vestibular illusions, as well as for certain mental states, to develop.

The most common illusion is the "leans", experienced by most pilots in a light or disturbing form.

The most dangerous is the "loss of situational awareness", which is caused by a high workload and channelized attention during aircombat without well defined horizon. This phenomenon led to the most near accidents.

Other causes of near accidents are false perception of height, false sensation of bank during low level manoeuvres, and target fixation.

The disorientation is in most cases detected by "instinct", with the detection of an unexpected attitude on the attitude indicator during a crosscheck taking a second place far behind.

One third of the most serious incidents were a serious risk for flight safety and 5-8% of the aviators experiencing a near accident, due to disorientation, every year.

73% of the aviators mentions to be more susceptible for disorientation during flying in the F16 than in another aircraft, especially while flying at night, under IMC or in aircombat. The reasons are: The high sitting position under a frameless canopy without aircraft reference; little feedback and sensation of speed; high manoeuvrebility with high Gz-onset and lineair acceleration; small HUD with difficult interpretation; a poor cockpit layout with small instruments and large necessary headmovements; and the mission requirements wich cause a high workload.

To prevent future disorientation incidents and accidents the crosscheck should be improved and the workload lowered. Also technical improvements are needed. This can be reached by:

A. Better and more briefings on the subject, with realistic material.
B. Inflight and, realistic, groundbased demonstrations.
C. Regular and better IF training.
D. More flying hours.
E. Better supervision and no pushing of unexperienced pilots.
F. Less reflecting materials.
G. A wide angle HUD, with better information presentation.
H. A better cockpit layout, with the inflight stress management system up front, and larger instruments.
I. Several technical improvements, like a terrain reference system, a ground avoidance system and, perhaps, a dual F16 for "all weather" missions.

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A METHODOLOGY FOR THE OBJECTIVE MEASUREMENT OF PILOT SITUATION AWARENESS

by

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SUMMARY

The ability of the pilot to maintain situation awareness is recognized in the pilot community as crucial to mission success and survivability. The design of the pilot vehicle interface must therefore be guided by the goal of maintaining and enhancing pilot situation awareness. A formal definition of situation awareness is presented in addition to a detailed description of the Situation Awareness Global Assessment Technique (SAGAT). SAGAT was developed as an objective measure of a pilot's situation awareness, including pilot knowledge of ownship status, the tactical environment, his overall comprehension of the situation, and his ability to project the tactical situation into the near future. SAGAT allows for a variety of system design concepts to be evaluated on the basis of situation awareness, as well as workload and performance, thus providing the design community with a much needed tool.

INTRODUCTION

Situation awareness (SA), the pilot's knowledge of the world around him and his place in it, has become a design goal of major importance in the past few years. Research is flourishing in many areas, including:

1.) sensor technology and sensor integration,

2.) advanced control and display devices - head-up displays (HUD), helmet mounted displays/sights (HMD/HMS), voice activated controls, touch sensitive display screens, panoramic and virtual display concepts,

3.) integrated, symbolic, color and three-dimensional display formats,

4.) automation of pilot tasks through expert systems/artificial intelligence, and

5.) intelligent aircraft systems for integrating, prioritizing, filtering, and communicating information to the pilot in a timely, situationally appropriate manner.

All of this research has one goal in common: to improve some aspect of pilot situation awareness, and thus, hopefully, his overall mission performance and survivability. Designers and researchers in these areas have been hampered by two major problems, however. First, a common, consistent definition of situation awareness is needed. A researcher concentrating on spatial awareness, for instance, must be aware of how this aspect of SA interacts with the pilot's simultaneous desire to obtain awareness of other aircraft in the environment. A researcher designing an expert system for the cockpit needs to know just what aspects of the situation are important and when. As most people working in this area have discovered, this is not a trivial problem. A precise definition and detailed understanding of situation awareness is required.

The second major problem hindering researchers has been the lack of an objective technique for evaluating competing design concepts. Subjective techniques for evaluating SA (e.g. rate your SA on a 1 to 10 scale) have serious short comings. Since the pilot does not know what is really happening in the environment, his ability to estimate his own SA is quite limited. A pilot may think he has perfect SA and be totally unaware of the enemy aircraft on his tail, his depleted fuel state, or a slight, but lethal, pitch down.

If a pilot is asked to subjectively evaluate his SA in a debriefing session, his rating may also be highly tainted by the outcome of the mission. When performance is favorable, whether through good SA or good luck, the pilot will most likely report good SA, and vice-versa. Furthermore, as this information is gathered after the run, the pilot will probably be inclined to rationalize and over generalize about his SA, as has been shown to be the case when information about mental processes is collected after the fact [15].

While performance is always the "bottom-line" criterion, much of pilot performance in the tactical environment is, by nature, highly variable and subject to the influence of many other factors besides SA. In other words, a new system may provide the pilot with better SA, but in evaluation testing this fact can be easily masked by excessive workloads or poor decision making if overall mission performance is used as the only dependant measure. The second problem with this type of approach stems from the interactive nature of situation awareness sub-components. It is quite easy for pilots to bias their attention to a single issue which is under evaluation. However, improved SA in one area may easily result in decreased SA in others, yielding misleading results if only one issue is examined at a time. What researchers really need to know is: how much SA do pilots have when taxed with all of the multiple, competing demands upon their attention that occur in flight.

For this reason, a global, objective measure of SA is important. To improve pilot situation awareness, designers need to be able to evaluate the impact of design concepts on SA directly. Only through scientific, objective evaluation of these many concepts (and resultant concept refinements), can the desired improvements in pilot SA be realized.

It is the purpose of this paper to present the results of ongoing research at Northrop in the area of situation awareness definition and measurement.

SITUATION AWARENESS DEFINITION

A model of pilot decision making is presented in Figure 1. It is the pilot's situation awareness, his mental model of the world around him and his place in it, that directs his decision making and tactical performance. Situation awareness forms the critical input to, but is separate from, pilot decision making, which is the basis for all subsequent pilot actions. Even the best trained and most experienced pilots can make the wrong decisions if they have incomplete or inaccurate SA. Conversely, a pilot may accurately understand what is occurring in the environment, yet not know the correct action to take or be unable carry out that action. For this reason, it is important that SA be considered separately from decision making and performance.

The pilot's SA is derived from a number of sources including the aircraft interface, communications with other aircraft, and the environment directly. The quality of a pilot's SA is moderated by his personal capabilities (a product of his inherent abilities, training, and experience), his preconceptions and objectives (typically established in the pre-mission briefing), and his ongoing task workload.

The SA construct itself can be broken down into three levels, as is depicted in Figure 1.

<u>Level 1 SA</u> - The pilot perceives the elements (e.g. an aircraft, a mountain, a warning light) that are present in the environment, along with their relevant characteristics (e.g. color, size, speed, location).

<u>Level 2 SA</u> - Based upon his knowledge of these elements, particularly when put together to form patterns with the other elements (gestalt), the pilot forms a holistic picture of the environment, comprehending the significance of objects and events For example, the pilot not only detects that a red light has appeared on the warning panel, but he also comprehends that the appearance of that light indicates the failure of a particular system which is life threatening. He comprehends that the appearance of three enemy aircraft within a certain proximity of each other and in a certain geographical location indicates certain things about their objectives, which, in turn, leads to a projection of possible future scenarios.

<u>Level 3 SA</u> - It is the ability to project the future actions of the elements in the environment, at least in the very near term, that forms the third and highest level of situation awareness. For example, knowing that a threat aircraft is currently offensive and is in a certain location allows the pilot to project that the threat aircraft is likely to attack in a given manner. This gives him the knowledge (and time) necessary to decide on the most favorable course of action to meet his objectives.

Interviews with pilots indicate that a common set of elements is appropriate across a wide variety of tactical missions and mission segments. Due to changing situations and objectives, the relative importance of each of these variables changes over time, however. At any point in time there is a subset of this information which is primary and the remainder which is secondary, but still of some importance. A classic example of this point occurs when a pilot becomes heavily involved in defeating a missile. He may fail to pay attention to his flight parameters and consequently fly into the ground, even though he is successful at his primary task of defeating the missile. It is clear in this instance that while information concerning the airborne missile is of primary importance, other information is also important, just secondary. The attentional narrowing brought on by high workload led to an unacceptable and lethal decrease in SA.

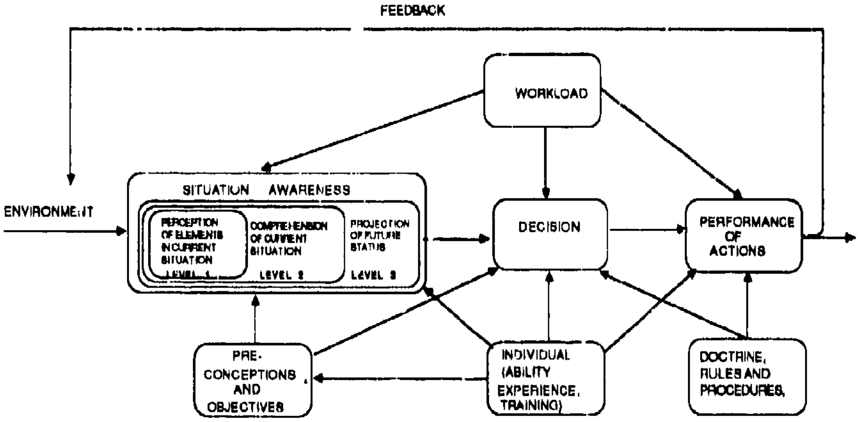


FIGURE 1 PILOT DECISION MAKING MODEL

From this description, SA is defined formally as:

> *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future".*

The elements in this definition have been explicitly defined for air-to-air tactical missions through task analysis and extensive interviews with pilots. Elements fall into the following categories:

1) AIRCRAFT - knowledge of ownship, friendlies, and enemies, including their location, weapons, system, and spatial attributes;

2) GROUND - knowledge of ground forces, terrain, features and reference points;

3) MISSILES - knowledge of airborne missiles, their location and status;

4) COMPREHENSION - higher level comprehension of the situation such as priority/imminence of threats, advantages/disadvantages, threat knowledge, capabilities and objectives; and

5) PROJECTION - projection of friendly and threat actions in the near future.

The perception elements, comprehension and projection requirements can also be described explicitly for different missions and aircraft types.

This definition has several implications. First of all, it is important that the pilot understand the situation, as well as merely perceive it. A novice may be able to detect red warning lights or enemy planes, but the pilot with true SA will know the detailed implications of a given system failure (e.g. possible causes, impacts on other systems, importance to the mission and survivability) and will comprehend enemy tactics and intentions based on aircraft formations and location. The really expert pilot will be able to project future events based on current parameters. He can operate in an active rather than reactive mode if he can "think ahead of the aircraft". Designers need to be aware of these higher level SA needs, not just individual elements, if we are to help pilots over the information proliferation problem which is currently engulfing them.

Secondly, there truly is a large number of elements that pilots are required to attend to, in order to achieve SA. They need to be aware of navigational and spatial arrangements of themselves and ground references. They need to simultaneously be aware of ownship capabilities and flight parameters and those of many others in the tactical environment, both friendly and enemy. To achieve this, pilots often rely on information sampling and the use of selective attention. Pilots can easily be the victim of their own coping strategies, however, since, "attentional narrowing", the tendency to focus on singular aspects of the situation during high workload, can result in a lethal loss of SA in other areas. Designers face the challenge of providing the pilot with the detailed SA he needs for specific tasks, while simultaneously maintaining a high level of overall SA, within workload constraints. Design concepts which fail to take into account this collective need for SA across many areas will inadvertently limit pilot SA in an unacceptable manner.

COGNITIVE FOUNDATIONS

So, how do pilots manage to achieve SA under such demanding circumstances? A limited capacity, serial processing model is depicted in Figure 2, as one possible framework for understanding the SA process (modified from Wickens[19]). The environment is initially processed preattentively by the pilot through parallel iconic and echoic memory stores (sensory registers for visual and audio input to the brain). Certain properties will be observed at this stage, providing cues for further localized attention. The pilot may choose to direct his attention towards certain objects in the environment based upon characteristics such as location, shape, color or movement .

Further processing of these objects/features will typically be directed by their saliency with respect to the goals, objectives and tasks currently active in working memory and by their saliency in light of pertinent schema active in long term memory. Schema are memory stores which organize bodies of knowledge into integrated meaningful frameworks. Schema can provide coherent frameworks of understanding, encompassing highly complex system components, states and functioning. For instance, a schema for "missile employment" might include: dynamic relative positions of own and threat aircraft (location, altitude, airspeed, heading, flight path) and current weapon selection including weapon envelope/capabilities, current Pk, and rate of Pk change. If this schema was active, the pilot would be inclined to seek out and process those portions of the environment which were required by the schema.

Hayes, Waterman and Robinson [10] and Robinson and Hayes [17] found that schema will be used to make judgements concerning which information is relevant to a problem. Hinsley, Hayes and Simon [11] found that people will categorize information almost immediately into a schema that directs problem solving.

In addition, the pilot SA/decision making process can be viewed as a dual process whereby active schema and scripts are dictating which information to focalize attention on (conceptually driven), and simultaneously the presence of certain objects or attributes in the environment will activate new schema in long-term memory (data driven) [1]. If the pilot detected a new threat, for example, he might cease to operate on the "missile employment" schema, and a "threat assessment" schema might be activated.

The schema selected, when detailed enough, can be used to direct situation comprehension, future projection, and decision making. A "threat assessment schema" might include information as to what patterns of threats and threat movements constitute offensive versus defensive activities, for example. Future threat movements might be predictable from the schema through a classification of current threat movements into known tactics. Appropriate tactics for countering given threat actions might also be resident in the schema, greatly simplifying decision making.

Ties between the schema and scripts, sequences of appropriate actions for task performance, will also greatly facilitate the cognitive process. The pilot will not have to actively decide on appropriate actions at every turn, but will automatically know the actions to take for a given situation.

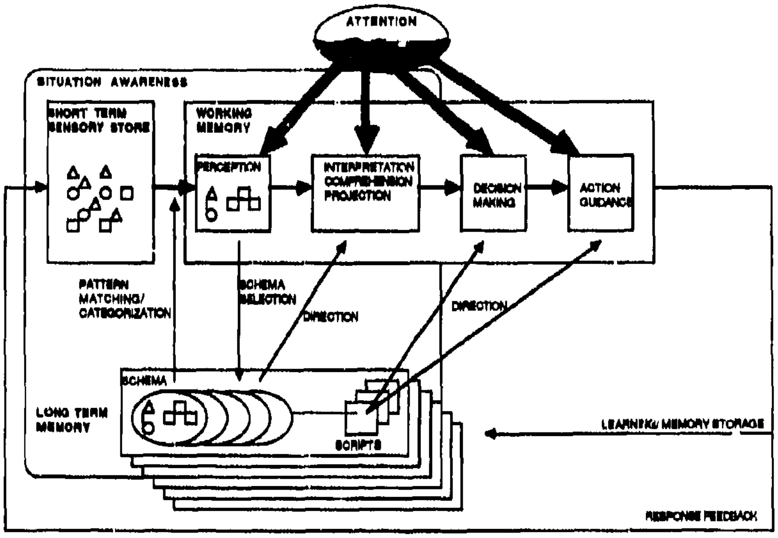


FIGURE 2 MECHANISMS OF SITUATION AWARENESS

When schema are not present to draw upon, working memory will be heavily loaded, as active processing will be required to comprehend, project, and carry-out decision activities. Fracker [8] has hypothesized that working memory constitutes the main bottleneck for situation awareness. Hartman and Secrist [9] have proposed that highly experienced pilots will use largely automated processes (such as an automated perception/action sequence directed by long term memory) to circumvent the limitations of working memory. (The risk of extensive automatic processing is that it tends to proceed with limited use of feedback. Pilots may be less data responsive in such situations.)

Whereas novice pilots may have to rely on simple rules and heuristics (rules-of-thumb), the expert pilot will typically have a much richer base of information to draw upon, expressed in schema in long-term memory. These schema, detailing the relevant system components, attributes, and functioning in such a way as to provide cues for pattern matching to the schema, can provide predictability of system dynamics, and ties to appropriate scripts for situational outcomes. SA will be largely dependent upon the existence of well developed representations in long-term memory, detailing a model of the functioning of objects alone and with others in the environment and providing for the projection of future actions of that object. When such schema do not exist, SA will be limited by the constraints of working memory.

In the complex environment of the fighter pilot, attentional demands due to informational overload, complex decision making and multiple tasks can quickly exceed limited cognitive resource capacities. Problems with non-optimal information sampling, visual dominance, and attentional narrowing under such high demands also seriously limit pilot SA.

In summary, situation awareness is a complex process of perception and pattern matching greatly limited by working memory and attentional capacities. Attention sharing and automated processing may serve to alleviate these limitations to some degree. Overall, it can be seen that the combat pilot must develop SA on the basis of well founded and detailed schema or mental models of the environment if he is to be successful in his tasks.

A current challenge is to define and further understand the appropriate schema for good SA. A goal-directed task analysis was conducted towards this end, an example of which is shown in Figure 3. The SA required to support each goal/subobjective across a variety of air-to-air missions was described in detail. The next step in this ongoing effort will be to empirically validate these findings and construct more detailed mental models which take into account the interactions and relationships among the components. When such models can be constructed for all of the pilots major tasks, a major knowledge base for training and design decisions will be available.

SITUATION AWARENESS MEASUREMENT

The challenge of designing systems which enhance SA, given the complex, multi-dimensional nature of the construct, is great. To achieve this goal, designers need to be able to objectively evaluate design concepts' impact on pilot SA. The Situation Awareness Global Assessment Technique (SAGAT), has been developed [5], [6], [7] as an objective measure of pilot SA in manned simulations. SAGAT provides a comparison of the real situation (as it exists in the simulator) to the situation that the pilot perceives, his SA. SAGAT assesses pilot SA in the following manner:

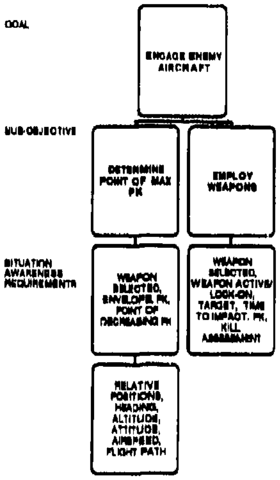


FIGURE 3 GOAL DIRECTED TASK ANALYSIS: ENGAGE ENEMY AIRCRAFT

- The pilot flies a mission scenario using a specified aircraft system in man-in-the-loop simulations.

- . At random points, the simulation is stopped and the cockpit and out-the-window displays are blanked.

- The pilot is asked a series of questions to determine his knowledge of the situation at that exact moment in time. The questions correspond to the pilot's specific SA requirements inclusive of perception, comprehension and projection elements. The SAGAT queries are currently programmed on a Macintosh computer, available at each pilot station, to allow for the rapid input and storage of highly spatial information. An example of a SAGAT query is shown in Figure 4. Each query has been designed to allow for rapid pilot input by framing the questions and responses in a manner which is as compatible with pilot knowledge representations as possible.

- As it is impossible to query the pilot about all of his SA requirements in a given stop, a portion of the SA questions are randomly selected and asked of the pilot each time. This random sampling method provides consistency and statistical validity, thus allowing SA scores to be easily compared across trials, pilots, systems and missions. Some of the questions in any particular query pertain to highly important SA information and some of the questions pertain to more secondary SA information.
This prevents inadvertently cueing the pilot and keeps him from biasing his attention to issues under evaluation.

- At the completion of the trials, the query answers are evaluated on the basis of what was actually happening in the simulation. This is accomplished by comparing the pilot's answers to data collected from the simulation computers. (Where necessary this may be augmented by subjective evaluations from a team of expert pilots, e.g. for a determination of the priority threat.) The comparison of the real and perceived situation provides an objective measure of pilot SA.

Thus, SAGAT provides an objective, global measure of the pilot's SA. The Air-to-Air Tactical Version of SAGAT consists of 36 queries, inclusive of the pilot's knowledge of his ownship status and his awareness of the location and attributes of his opponents, his higher level comprehension of the situation, and his ability to project future states of the tactical environment. By objectively evaluating pilot SA, and using this information to select and refine design concepts and overall aircraft system design, the goal of optimizing pilot SA can become achievable.

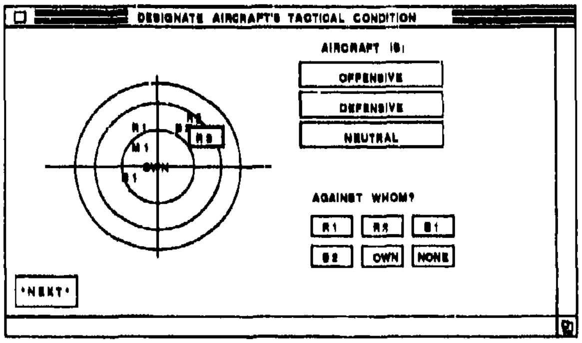


FIGURE 4 SAGAT QUERY EXAMPLE

Research at Northrop over the past several years has been directed at validating that SA information can be collected by this type of method and at determining the exact conditions under which it should be administered. In determining whether SA information will be reportable via the SAGAT methodology, several possibilities must be considered:

1) Data may be processed by subjects in short term memory (STM), never reaching long term memory (LTM). In this case, information would not be available during any SAGAT testing which exceeded the STM storage limitations (approximately 30 seconds with no rehearsal). If a sequential information processing model is used, then it is possible that information might enter into STM and never be stored in LTM where it would be available for retrieval. There is a good deal of evidence, however, that STM may not precede LTM, but merely be an activated subset of LTM [3], [14], [16]. In this type of model, information proceeds directly from sensory memory to LTM, which is necessary for pattern recognition and coding. Only those portions of the environment which are salient are then highlighted in STM (either through focalized attention or automatic activation). This type of model would predict that SA information which has been perceived and/or further processed by the pilot would exist in LTM stores and thus be available for recall during SAGAT testing which exceeds 30 seconds.

2.) The data may be processed in a highly automated fashion, and thus not be in the subject's awareness. Expert behavior can function in an automated processing/action sequence in some cases. Several authors have found that even when effortful processing is not used, the information is retained in LTM and is capable of affecting subject responses [12], [13], [16]. The type of questions used in SAGAT, providing cued-recall and categorical or scalar responses, should be receptive to retrieval of this type of information.

3.) The information may be in LTM, but not be easily recalled by the subjects. Evidence suggests that when effortful processing and awareness are used during the storage process, recall is enhanced [3]. SA, composed of highly relevant, attended to and processed information, should be most receptive to recall. In addition, the SAGAT battery, requiring categorical or scalar responses, is a cued recall task, as opposed to total recall, thus aiding retrieval. Under conditions of SAGAT testing, the subjects are aware that they may be asked to report their SA at any time. This too may aid in the storage and retrieval process. Since the SAGAT battery is administered immediately after the freeze in the simulation, no time for memory decay or competing event interference is allowed. Thus, the conditions should be optimized for the retrieval of the SA information. While it cannot be said conclusively that 100 percent of the subject's SA can be reflected in this manner, the vast majority should be reportable via the SAGAT technique.

To investigate these issues and others surrounding the use of this technique, two studies were conducted.

STUDY 1 - A study was conducted to determine how long after a "freeze" in the simulation SA information could be obtained from the pilot. A set of air-to-air engagements was conducted in Northrop's manned interactive multi-engagement simulator facility. A fighter sweep mission with a two versus four force ratio was used for the trials. Fifteen trials were conducted. At a random point in each trial, the simulator was "frozen" and SAGAT data immediately collected from all six participants, providing approximately 90 data points per query. The subjects were all experienced fighter pilots currently employed by Northrop. All subjects answered all the queries in the SAGAT battery in a random order at each stop. (Each query was therefore asked at a variety times after the stop across subjects and trials.) Following the completion of the SAGAT battery, a new trial was begun.

The SAGAT data was analyzed to determine at what point SA components decayed in the subjects' memory. It was hypothesized that Level 1 SA components would deteriorate fairly rapidly, and only Level 2 and 3 SA components would be accessible for longer periods of time, as this information would be more highly processed. The results of the study, an example of which is shown in Figure 5 did not reveal the expected decay for Level 1 components, however, even when a given query was answered five or six minutes after the break in the simulation. Similarly, Level 2 and 3 components did not reveal a decay over the SAGAT testing period.

Two explanations can be offered for these findings. First, this study investigated expert subjects' knowledge of information which was extremely important to task performance during a realistic simulation of those tasks. Most laboratory studies which predict fairly rapid decay times (approximately 30 seconds for short-term memory) typically employ the use of stimuli which have little or no inherent meaning to the subject (nonsense words or pictures). The storage and utilization of relevant information may be quite different than that of irrelevant information [2].

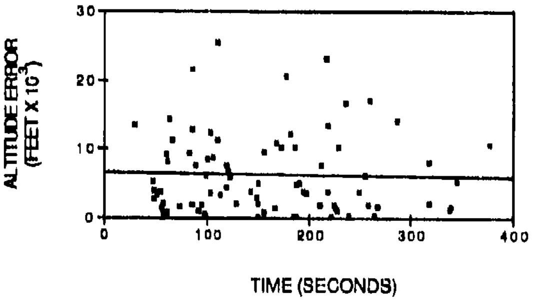


FIGURE 5 KNOWLEDGE OF OWNSHIP ALTITUDE
AS A FUNCTION OF TIME AFTER STOP
IN THE SIMULATION

Second, the results indicate that the SA information was obtainable from long-term memory stores. If schema, or other mechanisms, were used to organize SA information (as opposed to working memory processes only), then that information would be resident in long-term memory (LTM). The fact that Level 1 information was resident in LTM as well as Level 2 and 3 components indicates that either: (1) the inputs to higher level processing were retained as well as the outputs, or (2) the Level 1 components were retained as important pieces of pilot SA in their own right and are significant components of LTM schema (e.g. target altitude itself is important to know and not just the implications of target altitude). Both of these explanations may be correct. These findings support the predictions of a processing model in which information passes into LTM stores before being highlighted in STM.

(As a caveat it should be noted that the subjects were actively working with their SA knowledge by answering the SAGAT queries for the entire period that the simulation was stopped. No intervening period of waiting nor any competing activity was introduced prior to administering any SAGAT query. The pilot's knowledge of SA information may be interfered with if time delays or other activities (particularly flight tasks) are imposed before SAGAT is administered.)

The major implication of these results is that, under these conditions, SA data is readily obtainable through the SAGAT technique for a considerable period of time, up to 5 or 6 minutes, after a stop in the simulation.

STUDY 2 - A second study was initiated to address an issue of simulation practicality. Once a trial has been interrupted to collect this type of data, can it be resumed again, or must a new trial be started? To address this question, a set of air-to-air engagements were conducted in the same manned multiple-engagement simulator environment. A fighter sweep mission with a two versus four force ratio was used for the trials. Five subject teams completed the test matrix shown in Figure 6. The independent variables were duration of the stops (1/2, 1 and 2 minutes) and the frequency of stops (1, 2, or 3 times during the trial). Trials in which no stops occurred were used as a control. Each team participated twice in each condition. Conditions were administered in a random order. Pilot performance was collected as the dependent measure.

	FREQUENCY OF STOPS			
DURATION OF STOPS (MINUTES)	0	1	2	3
1/2	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5
1	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5
2	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5	TEAM 1 TEAM 1 TEAM 2 TEAM 2 TEAM 3 TEAM 3 TEAM 4 TEAM 4 TEAM 5 TEAM 5

FIGURE 6 STUDY 2 TEST MATRIX

As depicted in Figure 7, there was no significant difference in pilot performance ($\alpha = .05$) between trials in which there were stops to collect SAGAT data and those in which there were no stops. The number of stops during the trial, shown in Figure 8, had no significant impact on pilot performance ($\alpha = .05$), nor did the duration of the stop, as depicted in Figure 9. This would indicate that the stops to collect SAGAT data (as many as three for up to 2 minutes in duration) will not have a significant impact on later pilot performance. The lack of a significant influence of this procedure on pilot performance probably rests on the fact that the relevant schema are actively utilized by subjects during the entire freeze period. Under these conditions, the pilot's SA does not have a chance to decay before the simulation is resumed. Thus, their SA is fairly intact when the simulation continues, allowing them to proceed with their flight tasks where they left off.

These results are being viewed with some caution. More such tests are probably needed to assess with certainty that the freeze and restart does not influence subsequent performance. Subjectively, the pilots did fairly well with this procedure, and were able to readily pick up the battle where they left off. The recommendation for SAGAT administration at this point is that if SAGAT data is collected in this manner, some trials should be conducted during which SAGAT is not collected, so that a check is provided for any influences that a freeze and restart in the simulation may cause. SAGAT may still be administered without restarting the trial afterwards, if assessment of SA is the primary objective.

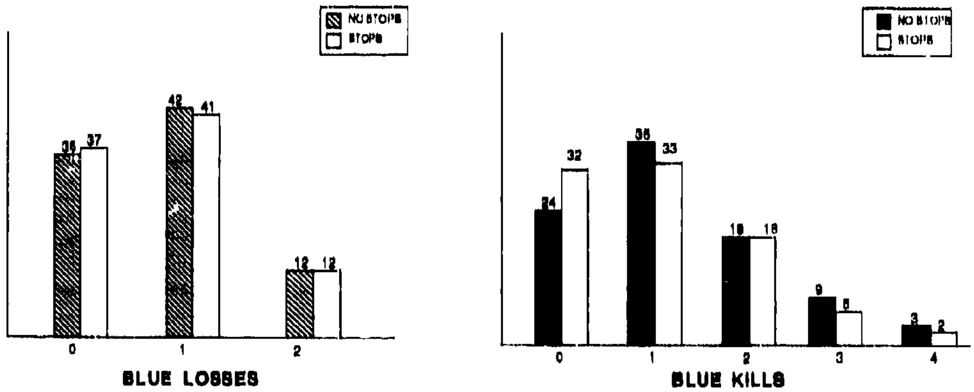
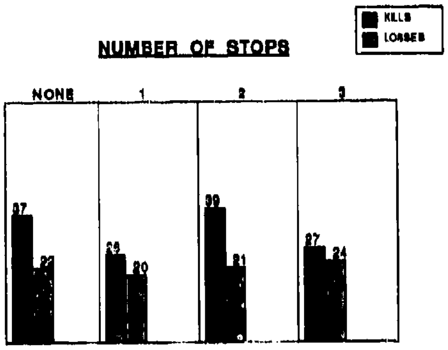
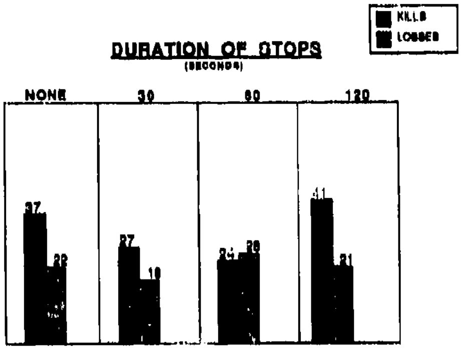


FIGURE 7 PILOT PERFORMANCE



N = 30 TRIALS PER CELL

FIGURE 8 EFFECT OF NUMBER OF STOPS ON PERFORMANCE



N = 30 TRIALS PER CELL

FIGURE 9 EFFECT OF DURATION OF STOP ON PERFORMANCE

RESEARCH IN SITUATION AWARENESS

With a concrete definition of SA and a tool for measuring SA, much new research can be conducted.

DESIGN - The many new and promising technologies and concepts being considered with the hope of improving pilot SA can be developed, evaluated, and refined to best meet that need, including: 1) avionics systems, 2) advanced control and display devices, 3) display formats, and 4) AI/expert systems for the cockpit. To date SAGAT has been used to assess alternative sensor configurations, display hardware options and new tactical situation display formats. In each of these cases, it provided new insights into design issues surrounding these concepts.

TRAINING - The goal of improving pilot situation awareness can be met by incorporating SA into training programs in several ways. (See Endsley [4] for a detailed discussion).

1) SAGAT provides a criterion measure for directly evaluating training programs and assessing pilot achievement.

2.) SA-oriented training programs can be developed that instruct pilots in the components of important schema, the dynamics and functioning of tactical elements and projection of future actions based on these dynamics. This type of SA-oriented training is greatly needed to supplement traditional technology-oriented training.

3.) Feedback is an important component of the learning process. The SAGAT technique can be modified to provide feedback to pilots on their SA during simulations. This type of training would allow pilots to understand their mistakes and better assess and interpret the environment.

4.) SA is not a passive process. Pilots must actively work to achieve it. The skills required for achieving and maintaining good SA need to be identified and formally taught in the training program.

CONSTRUCT EXPLORATION - There is much that is currently not known about SA. Which components are most important? What is the composition of mental models? What makes one pilot so much better than another? How is higher level SA generated from lower level components?

SAGAT is currently being used to begin to answer these type of questions. In an attempt to ascertain why some pilots are better at SA than others, research is currently under way to compare pilot abilities at SA to a set of measures assessing their abilities in a number of areas which are hypothesized to have some importance to SA, including:

1) Spatial abilities - the degree to which an individual can mentally visualize and manipulate objects spatially as well as one's own orientation relative to the objects (spatial mapping).

2) Perceptual abilities - including vigilance, perceptual speed, encoding speed, and pattern recognition.

3) Attention abilities - including selective attention capacity, and attention sharing ability.

4) Logical abilities - including general analytic capabilities, and capabilities for predicting system functioning and assessing and diagnosing patterns.

5) Personality factors - Specifically, cognitive complexity and field-independence, since these have been related to problem solving and workload management.

6) Memory - including short-term memory capacity.

In a separate study, individual SA components are being correlated with performance scores to determine which components are most important. Ongoing research is exploring the mental models pilots use to perform their tasks. A great deal more research of this type is needed, if designers and engineers are to be highly effective in the goal of improving SA.

CONCLUSION

The potential for enhancing pilot SA through well developed aircraft designs and training programs hinges on an objective evaluation program that considers the global SA requirements of the pilot. By carefully defining SA and using this knowledge to design integrated aircraft systems that meet the dynamic needs of the pilot, great improvements in mission performance/survivability will be possible.

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SITUATIONAL AWARENESS RATING TECHNIQUE (SART): THE DEVELOPMENT OF A TOOL FOR AIRCREW SYSTEMS DESIGN

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SUMMARY

Human engineering activities in aircrew system design traditionally have been concerned with the reduction and management of operator workload. Recent advances in automation technology have radically changed the role of the human operator and highlighted the essential human function for making adaptive decisions in situations involving uncertainty. Improving and enhancing operator 'situational awareness' has become the major crew station design driver for achieving survivability and mission effectiveness criteria. The purpose of the research reported in this paper is to investigate how aircrew understand "situational awareness" (SA) and to develop tools for its subjective estimation.

1. INTRODUCTION

Situational awareness is a relatively new concern in human factors (1,2). Its origins are probably in aircrew jargon - some say USAF F15 operators - because they need it and sometimes lack it. Based on a series of interviews with air combat experts, in 1979 KELLY et al (3) developed a taxonomy of skills, traits and performance measures important for air-to-air combat which included aggressiveness, decisiveness, hands-on flying skills, knowledge, ability and "situation awareness" which was described as "probably the sum of numerous perceptual and cognitive skills".

Operational requirements for situational awareness have implications for flight safety as well as combat effectiveness. In 1984, "Loss of situational awareness" was cited as a probable contributory factor in 20 out of 41 USAF operator-factor accident reviews (4). Loss of SA is related to and a potential contributor to spatial disorientation (SDO). However, SA is intended to be the broader term, encompassing more than spatial disorientation references, and including more clearly psychological aspects of attention and cognition as well as sensory physiology considerations. Recent accidents in advanced single-seat tactical fighter aircraft (F16,F18) involving controlled flight into terrain (CFIT) have prompted concern over loss of "attitude awareness" (5). In these accidents, the pilots seem to have collided unknowingly with the ground under circumstances not typically associated with SDO visual/vestibular conflict.

Awareness problems in advanced aircraft have important implications for crew-systems design and crew training. The major crew system integration implications concern the role of automation, its effect on operator functionality, and the management and cognitive quality of cockpit information. In retrospect, it seems inexcusable that advanced systems, such as the F16 and F18, can sense impending ground impact from height, speed and attitude data, and yet fail to communicate the situation to the pilot. The major training implications of awareness problems concern task prioritisation and attention management procedures. Much of the CFIT debate has focused on the usability and priority of HUD and ADI attitude references. It is disappointing that even after over 20 years flying experience there is still uncertainty about whether or not the HUD should be used as a primary flight reference.

Losing situational awareness has much in common with the factors contributing to geographical disorientation (6). Therefore, it is not surprising that improving situational awareness was recognised as a crew-system integration objective out of research on the design of advanced aircraft tactical situation displays. Looking forward to the cockpit of the year 2000, Reising and Emerson (7) noted that "the key advantage of pictorial formats is to provide the pilot with situational awareness not only in the tactical area, but also in all areas which are important for the successful completion of the mission". Notwithstanding the F16/F18 experiences, it should be possible to enhance pilot awareness by design if advanced automation and control/display technology are harnessed and applied using good engineering psychology practice. The potential in technology for enhancing pilot situational awareness intuitively, by design, without major training penalties, is identified as the major design driver behind advanced crew systems programs, such as Super Cockpit (8) and Pilots Associate (9). These programs aim to couple advanced AI computing techniques for mission and information management with intuitive 3-D virtual interfaces, pictorial formats and voice technology. This successful integration to form an "electronic crewmember" is intended to improve the pilot's situational awareness leading to improved decision-making, survivability and combat effectiveness.

Situational awareness is probably the pre-requisite state of knowledge for making adaptive decisions in situations involving uncertainty i.e. a veridical model of reality. As such, it creates the potential for behaving adaptively up to a knowledge based level, if only by trial and error minimisation. Since situational awareness is probably not a permanent nor a universally achieved state, it is understandable that there is uncertainty about what it means and about how it is created. Definitions of situational awareness are probably about as useful as lectures for octogenarians on how to evacuate eggs. This may be, as William James wrote in 1890 about definitions of attention, "Everyone knows what attention is..." His description of the antithesis is probably more interesting: "...the confused, dazed and scatterbrained state" (10). Notwithstanding, HQ USAF AFISC/SE Safety Investigation Workbook (AFP 127-1 Vol III 1986) defines Situational Awareness as "Keeping track of the prioritised significant events and conditions in one's environment." Confusion here may affect the sequence or priority of tasks to be performed (Getting behind the power curve)." Put more bluntly, and focusing on process rather than state implications, situational awareness means "What-on-earth-is-going-on?" (11). Other more pragmatic definitions describe relevant knowledge sources, e.g. "the crew's knowledge of both the internal and external status of the aircraft, as well as the environment in which it is operating" (12). The USAF Tactical Air Command definition (13) identifies five sources of relevant knowledge:

(a) Knowing where the friendlies are and what they are doing.
(b) Knowing where the threats are and what they are doing.
(c) Knowing what my flight knows and our options for attack/defence.
(d) Knowing what other flights know and what their intentions are.
(e) Knowing what part of the above is not known or is missing.

Knowledge state descriptions involve a degree of specificity which may be inappropriate for other situations and tasks. They also raise the issue of the organisation and structure of knowledge, in particular the role of implicit and explicit knowledge. Knowing what is not known is not a new concern. It was once addressed under the aetiology of "unawareness mistakes" (14,15). Unawareness errors continue to interest accident researchers (16). Recently, research has identified the dissociation between the performance of complex skills and the ability to make explicit, through verbal expression, conscious declarative knowledge of the tasks. The knowledge related to self-taught skills is frequently unavailable to conscious thought or verbal expression (17,18).

A comprehensive understanding of SA needs to take into account the active, dynamic characteristics of the process of maintaining awareness, as well as the role of knowledge structures in decision-making. Morshinge and Retelle (19), in a description of air combat and the Pilot's Associate program objectives, note that "Perhaps the key factor in the maturation of a fighter pilot is his ability to anticipate situations rather than simply to react to them". Failure to anticipate the danger in situations was identified as the primary cause of errors of inattention in the early Cambridge Cockpit studies on the disorganisation of behaviour (20). The validity of any understanding of aircrew jargon that relies on non-aircrew constructs will always be questionable. However, there clearly is work relevant to the understanding of situational awareness in research on human cognition such as on cognitive style (21), visualisation (22), models of human problem solving behaviour (23) and theories of attention (24).

The research strategy underlying the present study is influenced by experience with the workload paradigm. Optimising operator workload has been traditionally regarded as the Holy Grail of human engineering: A much sought after but never certainly achieved objective. Objective and subjective techniques for measuring workload abound, not in the least because it is a multifaceted, multidimensional construct (25,26). Subjective workload measures are used extensively during crew-systems integration activities because of their practical advantages (e.g. high face validity, ease of administration, low-intrusiveness) and their apparent sensitivity to changes in demand. They have mostly evolved pragmatically. Consequently, criticism of subjective workload methods has focused on considerations of validity, theoretical consistency and diagnostic power (27). Enhancing situational awareness would seem to be, at least at face value, a higher design objective than optimising operator workload, particularly for systems in which the essential human function is to make decisions in uncertainty. Optimum workload without situational awareness is probably more undesirable than the converse. The attractiveness of the awareness paradigm derives from its potential to focus more clearly on cognitive skills and on goals and intentions, rather than on activity-related analyses.

The intention of the present study is to derive methods for the subjective estimation of situational awareness in order to assist in the quantification and validation of design objectives for crew-systems integration. Like workload, situational awareness is probably a complex construct. Reliable predictions about decision-making performance are unlikely to be derived from single subjective measures of situational awareness. The intention is to use knowledge elicitation procedures to examine the dimensionality of aircrew constructs for situational awareness. It is hoped that this will achieve some construct validity for the estimation tools that emerge, since they are intended ultimately for aircrew use. Also, like workload estimation, the utility of subjective measures of situational awareness will depend on the contribution to decision-making performance of processes available to consciousness. The approach adopted thus rests on assumptions that human operators use some understanding of situations in making decisions, that this understanding is available to consciousness and that it can readily be made explicit and quantifiable.

2. METHOD

Eighty four Test and Operational RAF aircrew were interviewed in three phases: 1) Scenario Generation, 2) Construct Elicitation, 3) Construct Structure Validation. The interviews were semi-structured, conducted by psychologists according to a fixed protocol for knowledge elicitation, based on the Personal Construct/Repertory Grid Technique (28).

Interviews were supported by appropriate briefing material including a video film demonstrating advanced crew-systems integration concepts. The interviews took place at MOD(PE) Research Establishment (Royal Aerospace Establishment, Farnborough; Royal Aircraft Establishment, Bedford; A & AEE Boscombe Down) and at RAF Stations in UK and Germany (RAF Marham, RAF Laarbruch, RAF Bruggen).

2.1. SCENARIO GENERATION

Descriptions of flight scenarios involving SA were obtained from 10 test aircrew, mostly pilots, at RAE Farnborough and RAE Bedford, based on the following agreed working definition comprising both situational and awareness components:

"Situational awareness is the knowledge, cognition and anticipation of events, factors and variables affecting the safe, expedient and effective conduct of the mission".

The 43 scenarios obtained in this way were reduced to the set of 29 familiar, generic examples listed below.

F.1 LOW AWARENESS FLIGHT SCENARIOS:

1. Approaching to land at an unfamiliar airfield in poor weather in an unfamiliar aircraft fitted with poor handling qualities and displays.
2. In air combat over a smooth sea with a poor horizon, your opponent is unsighted.
3. On a low level transit sortie, you are flying over unfamiliar terrain with poor visibility, in an aircraft with inadequate handling qualities and displays.
4. In formation flight on a long duration transit at high level over sea.
5. Making a climbing accelerating turn on a hazy day when the ground is not clearly visible.
6. Whilst flying in formation in cloud as a wingman, you momentarily lose sight of your leader.
7. On a singleton low level transit sortie in VMC with no other task than transit from A to B.
8. Carrying out an exercise flown regularly over a familiar area.
9. Flying for a long period of time in an uncomfortable seat.
10. Flying a new aircraft with similar but different handling qualities to those already flown.
11. Whilst carrying out a routine repetitive task, a subtle but important change occurs in the environment which you do not notice.
12. Flying in formation in an unfamiliar aircraft working at the limit of your capacity.
13. You are flying in weather 3/8 puffy cloud and while completing an avoiding turn into the cloud, you have an extremely near miss with a glider.
14. On a night flying exercise, while attempting to change the radio frequency the initial input to the computer fails and consequently a long time is spent on the input.
15. On an instrument flying sortie, the autopilot fails whilst you are completing a manoeuvre.
16. You are crossing in combat with a similar aircraft, and through pulling g to gain the advantage, you overstretch your aircraft.
17. You are transiting at low level in formation and approaching bad weather. As leader, you attempt to penetrate the bad weather but then find you have to pull up and thus lose the integrity of the formation.
18. You complete a roll to the left but unknown to you your head-up display is frozen and so even though the rest of the instruments register the roll you attempt to roll again.

F.2 HIGH AWARENESS FLIGHT SCENARIOS:

1. Approaching to land in good weather at a familiar airfield, in a familiar aircraft fitted with good displays.
2. In air combat, you are behind your opponent and over a familiar area with good horizon and height cues.
3. In a single-seat aircraft, leading a 4 ship low level attack formation in poor visibility, approaching the Forward Edge of Battle Area with threat aircraft known to be in the vicinity.
4. Flying at low level through mountainous terrain wearing N.V.G.s.
5. You are nearing the end of a sortie and beginning the descent through cloud as approaching to land.
6. Flying straight and level at 20,000 ft on autopilot.
7. You are transiting at low level as leader in a 4 man formation and approaching bad weather. Call to close formation and turn to avoid.
8. Flying in deteriorating weather, an emergency occurs which requires a quick safe landing and so you turn towards the heading where, from the briefing, you knew the weather was OK.
9. On a low level transit sortie, you are flying over familiar terrain in good weather in an aircraft with good displays.
10. In manoeuvring flight, a fault occurs and you immediately recover your aircraft to a flight path and altitude which will lead to a safe haven.
11. On a general handling sortie, requiring a Ground Control Approach, maintaining position in the instrument pattern with four other aircraft overhead and a new controller.

2.2. CONSTRUCT ELICITATION

The 29 selected scenarios were presented to 15 test aircrew, mostly pilots, at A & AEE Boscombe Down to elicit knowledge of generic constructs. Each construct was elicited using the Repertory Grid triadic method of presentation. Three randomly selected scenarios were presented to the aircrew subject on each occasion. The subject was asked to imagine being in each situation. Then the subject was required to identify two of the scenarios which contained something important for situational awareness, in accordance with the agreed working definition, that was not a feature of the other scenario. The subject was then required to identify the discriminating characteristic, and the construct thus elicited was recorded. The elicited construct was then used to define the poles of a 7-point scale on which all 29 scenarios were subsequently rated. Additional constructs were elicited using different triads of scenarios. The procedure was repeated with each subject until no more original constructs were readily elicited. A total of 44 SA construct dimensions with associated scenario ratings were obtained in this way, ranging from one to four constructs per subject. The 44 elicited SA constructs, and their associated rating dimensions are listed in Table 1.

TABLE 1. ELICITED CONSTRUCTS AND RATING DIMENSIONS

SUBJECT/ CONSTRUCT NUMBER	CONSTRUCT	DIMENSION
S1.01	Attentional load	A lot of things to attend to - Few things to attend to
S1.02	Concentration	Low level of concentration - High level of concentration
S2.01	Risk	Low risk of failure - High risk of failure
S3.01	Familiarity	Familiar - Unfamiliar
S3.02	Consciousness	Conscious decision - Instinctive decision
S3.03	Attention switching	Low degree of attention switching - High degree of attention switching
S3.04	Motivation	Low level of motivation - High level of motivation
S4.01	Arousal	Low level of arousal - High level of arousal
S4.02	Familiarity	Familiar - Unfamiliar
S4.03	Receptivity	Unreceptive to additional information - Receptive to additional information
S5.01	Info. quality	Poor information quality - Good information quality
S5.02	Info availability	No information available - All information available
S5.03	Stability	Dynamic situation - Static situation
S6.01	Workload	Low level of workload - High level of workload
S6.02	Spare capacity	Low capacity to monitor external events - High capacity to monitor external events
S6.03	Distraction	Undistracted from situation - Distracted from situation
S6.04	Arousal	Low level of arousal - High level of arousal
S7.01	Variability	Few variables - A lot of variables
S7.02	Concentration	Low level of concentration - High level of concentration
S8.01	Stability	Stable - Unstable
S8.02	Complexity	Complex situation - Simple situation
S8.03	Anticipation	Attention concentrated on present - Attention concentrated on future
S9.01	Demand	Demanding - Undemanding
S9.02	Info. quality	Poor quality references - Good quality references
S9.03	Concentration	Attention not concentrated on task - Attention concentrated on task
S10.01	Info. quality	Poor information quality - Good information quality
S10.02	Familiarity	Familiar - Unfamiliar
S11.01	Division of attention	Divided attention - Focused attention
S11.02	Complexity	Low complexity - High complexity
S11.03	Info. quantity	No useful information - A lot of useful information
S12.01	Spare capacity	No spare capacity - A lot of spare capacity
S12.02	Focusing	Unfocused attention - Focused attention
S12.03	Control	Have control - No control
S13.01	Familiarity	Familiar - Unfamiliar
S13.02	Focusing	Broad attention - Focused attention
S13.03	Complexity	Low complexity - High complexity
S13.04	Info. quality	Poor information quality - Good information quality
S14.01	Concentration	Low level of concentration - High level of concentration
S14.02	Risk	High possible future risk - No possible future risk
S14.03	Info. quality	Poor information quality - Good information quality
S14.04	Familiarity	Familiar - Unfamiliar
S15.01	Attentional demand	Low demand on attention - High demand on attention
S15.02	Predictability	Unpredictable - Predictable
S15.03	Focusing	Broad attention - Focused attention

2.3. CONSTRUCT RATINGS ANALYSIS

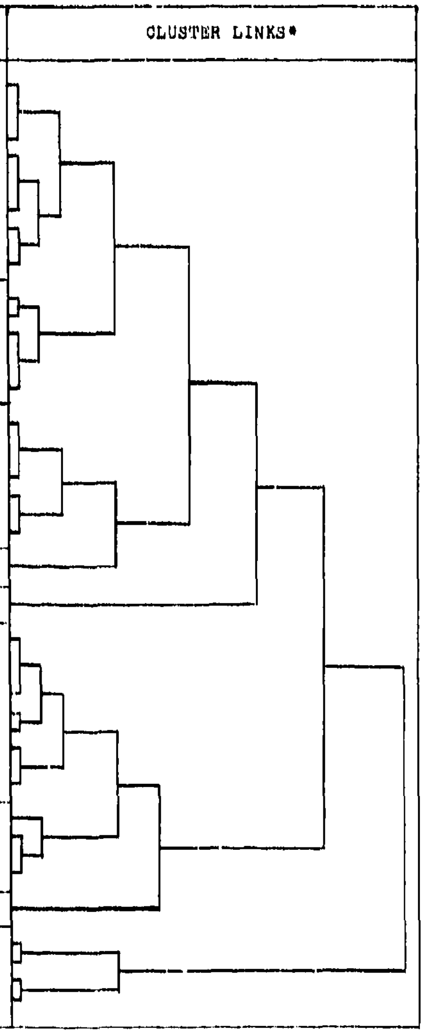
The structure of the elicited SA constructs was investigated by statistical analysis of construct/scenario ratings.

2.3.1. INITIAL CONSTRUCTS

Firstly, the construct/scenario ratings obtained during construct elicitation were subjected to Principal Components analysis with Varimax factor rotation. This analysis revealed that 4 components accounted for 65% of the total variability in the data. Constructs calculated as loading strongly on these 4 components are listed in Appendix Tables I-IV. The two major components, contributing 30% and 21% of the variance produced strong loadings for informational, attentional and, to a lesser extent, situational constructs. As a method of visualisation, the calculated loadings on the 4 factors were used to define a space which could be clustered using a single-link clustering algorithm based on Euclidean distance. The results are displayed in Figure 1. Guided by this analysis, generic constructs were selected for further evaluation using the criteria of elicitation frequency, strength of component loading and inter-correlation clustering. The 10 generic SA constructs selected in this way, with associated descriptions and dimensions, are listed in Table 2.

FIGURE 1. CORRELATION CLUSTERS

NO.	CONSTRUCT	COMPONENTS
S1.01	Attentional load	1
S9.01	Demand	1
S12.02	Focusing	1
S15.02	Predictability	1
S4.03	Receptivity	1
S6.02	Spare capacity	1
S9.02	Information quality	1
S12.01	Spare capacity	1
S5.02	Information availability	1
S6.01	Workload	1
S10.01	Information quality	1
S3.01	Familiarity	1,2
S13.01	Familiarity	1,2
S4.02	Familiarity	1
S8.02	Complexity	1
S8.01	Stability	1
S13.03	Complexity	
S5.03	Stability	3
S10.02	Familiarity	1
S14.02	Risk	3
S6.03	Distraction	
S13.02	Focusing	
S13.04	Information quality	1
S15.03	Focusing	3
S14.03	Information quality	3
S7.01	Variability	1
S1.02	Concentration	2
S4.01	Arousal	2
S6.04	Arousal	2
S12.03	Control	2
S7.02	Concentration	2,3
S9.03	Concentration	2
S3.03	Attention switching	
S15.01	Attentional demand	2
S11.03	Information quantity	2
S2.01	Risk	2
S11.01	Division of attention	2
S11.02	Complexity	2
S14.01	Concentration	2
S14.04	Familiarity	2
S3.02	Consciousness	4
S5.01	Information quality	
S3.04	Motivation	4
S8.03	Anticipation	4



* Link length inversely proportional to link strength

TABLE 2. GENERIC SITUATIONAL AWARENESS CONSTRUCTS

NO.	GENERIC CONSTRUCT	DIMENSION	DESCRIPTION	RELATED CONSTRUCTS
C1	Familiarity	Unfamiliar v Familiar situation	Degree of acquaintance with situation experience	S3.C1; S4.C1 S10.C2; S13.C1 S14.C4
C2	Focusing	Focused v Divided attention	Degree of distribution or focusing of one's perceptive abilities	S3.C3; S11.C1 S12.C2; S13.C2 S15.C3
C3	Information quantity	No v A lot of relevant information	Amount of knowledge received and understood	S5.C2; S11.C3
C4	Instability	Unstable v Stable situation	Likeliness of situation to change suddenly	S2.C1; S5.C3 S8.C1; S12.C3 S14.C2
C5	Concentration	Low level v High level of concentration	Degree to which one's thoughts are brought to bear on the situation	S1.C2; S6.C3 S7.C2; S8.C3 S9.C3; S14.C1
C6	Complexity	Simple v Complex situation	Degree of complication (number of closely connected parts) of situation	S8.C2; S11.C2 S13.C3
C7	Variability	Few v A lot of 'things' to attend to	Number of variables which require one's attention	S1.C1; S7.C1 S9.C1
C8	Arousal	Low level v High level of arousal	Degree to which one is ready for activity (sensory excitability)	S3.C4; S4.C1 S6.C4
C9	Information quality	Poor v Good quality of information	Degree of goodness or value of knowledge communicated	S5.C1; S10.C1 S13.C4; S14.C3
C10	Spare capacity	No v A lot of spare capacity	Amount of mental ability available to apply to new variables	S4.C3; S6.C1 S12.C1

2.3.2. GENERIC CONSTRUCTS

Next, the 10 generic SA constructs and 29 scenarios were presented to 10 test aircrew at RAE Farnborough for further scenario/construct ratings. The 29 scenarios were divided into two arbitrary sets. Five aircrew rated each set to give 2 independent sets of data. The ratings obtained are summarised in Appendix Tables V and VI, together with the results of an Analysis of Variance (ANOVA) across scenarios. The ANOVA results indicate the relative sensitivity of the constructs to the differences between the scenarios. Only Focusing (C2) and Information Quantity (C3) failed to achieve statistical significance (Set I scenarios only).

Both sets of ratings were subjected to Principal Components analysis with Varimax factor rotation. The resultant correlation matrices are reported in Appendix Tables VII and VIII. The Principal Components loadings are reported in Appendix Tables IX and X with a summary of the highly loaded constructs at Table 3. Three components accounted for 79% and 71% of the variance in the Scenario I and II sets respectively. In both data sets, Complexity (C6), Variability (C7) and Instability (C4) were strongly inter-correlated and loaded highly on the 1st Component. Similarly, Information Quantity and Information Quality were inter-correlated, and loaded highly on the 2nd Component in the Set I data, along with familiarity (C1), and loaded on the 3rd Component in the Set II data. Focusing (C2) loaded highly on the 3rd Component in the Set I data, and on the 2nd Component in the Set II data, along with Concentration (C5) and Arousal (C8). Spare Capacity (C10) was inter-correlated with Concentration (C5) and Arousal (C8), and loaded highly on the 1st Component in both data sets.

TABLE 3. CONSTRUCTS LOADING HIGHLY ON PRINCIPAL COMPONENTS FOR FLIGHT SCENARIOS

SCENARIO SET I		SCENARIO SET II	
1st Component (Var: 47.89%)		1st Component (Var: 36.52%)	
Arousal	0.919	Complexity	0.924
Concentration	0.914	Variability	0.915
Instability	-0.858	Spare capacity	-0.720
Complexity	0.849	Instability	-0.650
Spare capacity	-0.823	Arousal	0.607
Variability	-0.819	Concentration	0.571
2nd Component (Var: 19.75%)		2nd Component (Var: 20.15%)	
Information quantity	0.859	Focusing	0.859
Information quality	0.750	Concentration	-0.688
Familiarity	0.728	Arousal	-0.671
3rd Component (Var: 11.52%)		3rd Component (Var: 15.25%)	
Focusing	0.956	Information quantity	0.896
		Information quality	0.748

2.4. CONSTRUCT STRUCTURE VALIDATION

Guided by the analysis of the two independent sets of construct/scenario ratings, which showed similar data structures, and from an understanding of the theory of attention and cognition (29), on the basis of strength of component loading and inter-correlation clusters it was postulated that for purposes of simplification and theoretical consistency the SA constructs should be tentatively considered as comprising 3 broad categories or domains, namely:

(a) Demands on Attentional Resources (Instability, Complexity, Variability).

(b) Supply of Attentional Resources (Arousal, Concentration, Division of Attention, Spare Capacity).

(c) Understanding of the Situation (Information Quantity, Information Quality, Familiarity).

In order to examine the validity of this postulated structure, and to test its applicability to other situations, a further study was conducted using decision-making scenarios generated for an investigation of Human-Electronic Crew Teamwork (30).

2.4.1. VALIDATION METHOD

Descriptions of 12 scenarios involving tactical decision-making behaviour were obtained from eight operational Tornado aircrew at RAF Marham. Six scenarios concerned Navigator decisions and six concerned Pilot decisions. All the decisions in the scenarios were made without consultation with the second crew member. In each Pilot/Nav decision category, three scenarios described "High Trust" decisions and three scenarios described "Low Trust" decisions. Situational awareness was not a specified scenario variable. The 12 decision scenarios obtained in this way are described below.

PILOT DECISION SCENARIOS:

P1 EVASION: In a low level evasion scenario, the Pilot sees an enemy fighter in front. On the basis of ability to get a successful shot off, risk to own aircraft, ground threats, other air threats, hit probability and what the enemy will do if not killed first, without consultation, the Pilot decides to attempt a shot rather than to run away (HIGH NAVIGATOR TRUST).

P2 WEATHER: When flying low-level, the Pilot sees a potential weather problem ahead. On the basis of visual information on weather, and on terrain and map information, without consultation, the Pilot decides to change course right/left to avoid weather rather than to continue on course (HIGH NAVIGATOR TRUST).

P3 EW: When alerted by sidetone that a missile or electronic warfare threat is locked-on, the Pilot visually detects a missile. On the basis of the electronic visual strobe, electronic audio sidetone and visual information, without consultation, the Pilot decides to break right/left rather than to maintain course (HIGH NAVIGATOR TRUST).

P4 LOW LEVEL WEATHER ABORT: Flying at low-level with poor visibility conditions, the Nav considers that conditions are unfit to continue on course and queries whether it is safe to continue. On the basis of visibility, cloud base height, ground height and terrain shape, controlled airspace, safety altitude, without consultation, the Pilot decides to continue on course rather than to pull up (LOW NAVIGATOR TRUST).

P5 ROUTE CHANGE IN WEATHER: Flying low-level with bad weather ahead, the Pilot makes a late decision to turn left/right towards clearer weather area rather than maintain original course, without consulting the Nav regarding airspace restrictions (LOW NAVIGATOR TRUST).

P6 COUNTER STARBOARD: Flying low-level, with an enemy approaching unseen on starboard beam, on hearing a "counter-starboard" call from a buddy aircraft, without consultation, the Pilot decides to break port (LOW NAVIGATOR TRUST).

NAVIGATOR DECISION SCENARIOS:

N1 ROUTE CHANGE: In low-level combat, with the Pilot busy flying the aircraft, on basis of time, position, fuel and perceived threat, without consultation, the Nav calls a route change to come right/left, to cut short rather than extend route, to save rather than extend time and fuel (HIGH PILOT TRUST).

N2 AIR THREAT: In a combat formation of aircraft, the Nav perceives air threat in a threatening, firing position, loosing bullets. On the basis of disposition of own and enemy forces, position in space, perceived threat and assessment of likely actions by aggressor and counter threat success, without consultation, the Nav instructs the Pilot to weave, rather than buster (fast straight line), turn, climb, descend, drop bomb (for retard defence), chaff or flares (HIGH PILOT TRUST).

N3 COMMAND EJECTION: With the aircraft in a dive, and the Pilot not responding to 'recover' inputs, possibly suffering target fixation, and with ejection switch set to 'both', the Nav evaluates possibility of ground impact, lack of time, ground proximity and aircraft attitude, and chooses to eject rather than to take no action (HIGH PILOT TRUST).

N4 BOUNCE: When bounced on a pairs trip, the enemy fails to gain a good position and flies away out of view. Assuming that the bounce is over, the Nav decides not to continue to look out for return of the enemy, and without consultation, recommends the Pilot to return to track (LOW PILOT TRUST).

N5 WEATHER PENETRATION: Flying low-level in bad weather, the Pilot sees a hole (letter-box) under the weather, not observable from Nav's back-seat position. The Nav recommends the Pilot to pull-up to avoid the weather rather than continuing on course (LOW PILOT TRUST).

N6 RE-ROUTE: After being bounced, with Time-on-Target behind schedule, the Nav recommends the Pilot to speed up to cut corners and conserve fuel rather than re-route (LOW PILOT TRUST).

Next, the 12 decision scenarios were presented to 43 operational Tornado aircrew at RAF Laarbruch and RAF Bruggen for SA construct rating. Twenty four Pilots rated the 6 Pilot decision scenarios and 19 Navigators rated the 6 Navigator decision scenarios. Ratings were obtained on a 7-point rating scale - LOW (1) to HIGH (7) - for the 10 generic constructs, the 3 construct domains (Demand, Supply and Understanding) and the single dimension of Situational Awareness. The 14 constructs were presented and described as shown in Table 4.

TABLE 4. CONSTRUCTS FOR DECISION SCENARIO RATINGS

NO.	CONSTRUCT	DESCRIPTION
C.1	DEMANDS ON ATTENTIONAL RESOURCES	-
C.1.1	Instability of situation	Likeliness to change suddenly
C.1.2	Complexity of situation	Degree of complication
C.1.3	Variability of situation	Number of variables/factors changing
C.2	SUPPLY OF ATTENTIONAL RESOURCES	-
C.2.1	Arousal	Degree of alertness; readiness for activity
C.2.2	Concentration of attention	Degree to which thoughts are brought to bear
C.2.3	Division of attention	Distribution/spread of focus of attention
C.2.4	Spare mental capacity	Mental ability available for new variables
C.3	UNDERSTANDING OF SITUATION	-
C.3.1	Information quantity	Amount of knowledge received and understood
C.3.2	Information quality	Goodness or value of knowledge communicated
C.3.3	Familiarity	Degree of prior experience/knowledge
C.4	SITUATIONAL AWARENESS	Degree of situational awareness involved

2.4.2. VALIDATION RESULTS

The ratings obtained are summarised together with results of an ANOVA across scenarios in Appendix Tables XI and XII. The ANOVA results indicate that only Information Quality (C3.2) failed to achieve statistical significance (Pilot Decision Scenarios only). The additional postulated domain constructs - Demand (C1), Supply (C2), Understanding (C3) - and Situational Awareness (C4) were all sensitive to differences in the decision scenarios at the $p<0.05$ level.

Both sets of ratings were subjected to Principal Components Analysis with Varimax factor rotation. The resultant correlation matrices are reported in Appendix Tables XIII and XIV. The results of the Principal Components Analysis are reported in Appendix Tables XV and XVI, with a summary of the highly loaded constructs at Table 5. Four components accounted for 73% of the variance in both data sets. Both data sets exhibited similar structure. Instability (C1.1), Complexity (C1.2) and Variability (C13) were highly inter-correlated with Demand (C1) and all loaded highly on the same Principal Component. Arousal (C2.1) and Concentration (C2.2) were highly inter-correlated with Supply (C2) and to a lesser extent with Demand (C1), and all loaded highly on the Principal Component that accounted for the largest proportion of the variance. Information Quantity (C3.1) and Information Quality (C3.2) were highly inter-correlated with Understanding (C3) and to a lesser extent Situational Awareness (C4), and all loaded highly on the same Principal Component. Division (C2.3) and Spare Capacity (C2.4) were moderately inter-correlated with Familiarity (C3.3) and all loaded highly on the remaining Principal Component which accounted for the smallest proportion of the variance. However, it should be noted that Familiarity (C3.3) correlated positively with Understanding (C3) ($p<0.01$)) and that Spare Capacity (C2.4) correlated negatively with Demand (C1) ($p<0.001$).

The structure of the postulated construct domains showed some variation between the data sets. The correlations for the construct domains are shown in Tables 6 and 7. For Navigators, Understanding (C3) correlated with Supply (C2), and Situational Awareness (C4) correlated with all 3 construct domains. For Pilots, only Understanding (C3) correlated with Situational Awareness (C4). Generally, Demand (C1) positively correlated with Supply (C2), but only Understanding (C3) consistently correlated with Situational Awareness (C4).

TABLE 5. CONSTRUCTS LOADING HIGHLY ON PRINCIPAL COMPONENTS FOR DECISION SCENARIO

PILOT DECISIONS		NAV DECISIONS	
1st Component (Var: 22.10%)		1st Component (Var: 24.48%)	
Supply	0.826	Arousal	-0.894
Arousal	0.825	Concentration	-0.878
Concentration	0.809	Supply	-0.845
Demands	0.686	Demands	-0.591
2nd Component (Var: 19.69%)		2nd Component (Var:18.77%)	
Variability	0.830	Information quantity	-0.838
Complexity	0.807	Understanding	-0.833
Instability	0.774	Information quality	-0.815
Demands	0.496	Situational awareness	-0.501
3rd Component (Var: 18.89%)		3rd Component (Var: 16.27%)	
Information quantity	-0.899	Variability	0.885
Information quality	-0.795	Complexity	0.874
Situational awareness	-0.778	Instability	0.508
Understanding	-0.658	Demands	0.484
4th Component (Var: 12.61%)		4th Component (Var: 13.34%)	
Division	-0.820	Familiarity	-0.838
Familiarity	-0.696	Spare capacity	-0.695
Spare capacity	-0.635	Division	-0.651

TABLE 6. CORRELATION MATRIX OF DOMAIN CONSTRUCTS FOR PILOT DECISION SCENARIOS

NO.	CONSTRUCT	C1	C2	C3	C4
C1	Attentional Demand	1.000			
C2	Attentional Supply	0.601	1.000		
C3	Understanding	0.084	0.139	1.000	
C4	Situational Awareness	0.041	0.078	0.417	1.000

TABLE 7. CORRELATION MATRIX OF DOMAIN CONSTRUCTS FOR NAVIGATOR DECISION SCENARIOS

NO.	CONSTRUCT	C1	C2	C3	C4
C1	Attentional Demand	1.000			
C2	Attentional Supply	0.532	1.000		
C3	Understanding	0.133	0.489	1.000	
C4	Situational Awareness	0.497	0.649	0.557	1.000

3. DISCUSSION

Knowledge elicitation procedures indicate that three domains characterise aircrew situational awareness, namely Attentional Demands, Attentional Supply and Understanding. The study provides 10 aircrew constructs within these domains offering a deeper level of specificity. Quantification of these three construct domains is probably necessary and sufficient for a comprehensive measurement of SA. Uni-dimensional subjective estimation of SA offers little, if any, diagnostic power. A Situational Awareness Rating Technique (SART) can be proposed with alternative three-dimensional (3-D) and ten-dimensional (10-D) forms providing increasing specificity and diagnostic power. The most appropriate tool for a given application will depend on the degree of intrusiveness permitted by the measured task.

For highly dynamic real-time applications, such as flight simulation and flight trials, a relatively un-intrusive approach may be needed to minimise interference with the measured task. In such circumstances, the 3-D SART will be the more appropriate form, presented at intervals as a continuous or 7-point rating scale, or, with reduced visual and manual interference, as requiring a verbal report, such as LOW (1), MEDIUM (2) or HIGH (3) ratings, as in SWAT workload measurement (31). As an alternative to direct subjective estimation, conjoint scaling procedures or more simply, ipsative pair-wise comparisons could be used to calculate a uni-dimensional SA representation from the 3-D SART data. The 10-D SART will be a useful adjunct when a higher degree of specificity and diagnostic power is needed for projective and post hoc measurement of non-real time applications.

Whereas the 3-D SART probably offers the simplest multi-dimensional representation of SA - a 1-D or 2-D SART would be inadequate -- the necessity and sufficiency of the 10-D SART is governed by the requirements for specificity and diagnostic power. Fewer constructs would shorten the form and make it speedier to implement. Some semantically dissimilar constructs within domains are highly correlated in all data sets and appear to be redundant, namely: Complexity, Variability and Instability; Information Quantity and Information Quality; Arousal and Concentration. However, contraction across these constructs would reduce diagnostic power in situations and tasks where they are dissociated. On the other hand, alternative or additional domain constructs may improve diagnostic power for a particular application. Additional Understanding constructs could be particularly useful since, for decision-making scenarios at least, Understanding correlates highly with Situational Awareness. However, some caution should be exercised since arbitrary additions raise validity issues.

The 10-D SART is valuable because it is derived directly from aircrew constructs and this gives it validity as an aircrew tool. Some constructs are not always highly correlated within domains such as Concentration with Division of Attention, and Familiarity with Information Quantity. This is a good reason for their inclusion. Indeed, the decision scenario data suggest that one feature of the 3-D SART is that ratings of Supply may not be influenced by consideration of Division of Attention. Division, focusing, distribution and rate of switching of attention are important constructs that characterise the structure of attention or the attentional style. Dissimilar constructs and orthogonal dimensions are the source of diagnostic power.

Differences were found between the structure of the Pilots and Navigators 3-D SART data. These differences could be due to variations in content between the two sets of decision scenarios. However, this finding also raises the possibility that SART may be sensitive to differences in role playing and attentional/cognitive style (32). The relationship between self-awareness and situational awareness is probably important if both draw upon and compete for common resources. Demands on resources arising from self awareness may reduce the supply of resources for situational awareness, and vice versa. In life-threatening situations, situational awareness is probably affected by individual differences in psychological defence mechanisms, coping strategies and emotional/affective style (33,34). People who are terrified may not notice what is going on around them.

Further work is needed to demonstrate the applicability of SART to the measurement of situational awareness in real tasks. So far, the development of SART has been based on imaginary, though familiar, scenarios. Refinement of the SART scales through clarification of ambiguous working, standardisation of briefing, presentation procedures, data analysis and interpretation should be based on real task applications. Real task assessments are also needed to investigate the relationship between SA and task performance, and to check the primary assumption that situational awareness is important for decision-making. Experimental work is also needed to investigate the role of implicit and explicit knowledge in decision-making and to establish and improve the sensitivity of SART to knowledge variables.

Finally, it may be useful to use the SA paradigm and SART constructs to draw together some of the major implications for crew-systems integration. Situational Awareness and decision-making can be enhanced by systems design, or through the Electronic Crewmember, in three broad ways:

1. Control Demands on Attentional Resources This can be achieved by automation of unwanted workload, by fusing data and by reducing uncertainty.

2. Improve the Supply of Attentional Resources This can be achieved in several ways: a) By prioritising and cueing tasks to obtain the optimum attention-allocation strategy in accordance with mission goals and objectives; b) By organising the structure of tasks to exploit the available resource modalities; c) By maintaining pilot involvement and activity at the optimum level for resource availability.

3. Improve Understanding Methods for improving understanding by design include: a) By the presentation of information in cognitively compatible forms (3-D voice and pictorial multi-modal displays); b) By making accessible and sharing a wider knowledge base through knowledge communication/dialogue techniques such as interrogation, explanation and critiquing; c) By extension of the pilot's relevant experience by simulation training through mission planning and preview facilities.

4. CONCLUSIONS

Knowledge elicitation procedures can be used to identify aircrew constructs for structural awareness. Aircrew constructs provide a multi-dimensional characterisation of situational awareness consistent with the theory of attention and cognition. Rating scales for the subjective estimation of situational awareness can be derived from these constructs that are sensitive to differences in a variety of flight and tactical decision-making scenarios. The simplest representation of situational awareness comprises three dimensions or domains corresponding to constructs for situational demands on attentional resources, for the supply of attentional resources in response to situational demands, and for the understanding of the situation. Further research is needed with real tasks to investigate the diagnostic power of subjective estimation of situational awareness, and to refine the technique as a tool for aircrew systems design.

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7. APPENDIX

TABLE I. LOADINGS ON 1ST PRINCIPAL COMPONENT (VARIANCE: 29.77%)

NO.	CONSTRUCT	LOADING
S10.01	Information quality	-0.907
S6.02	Spare capacity	-0.893
S12.01	Spare capacity	-0.878
S4.03	Receptivity	-0.870
S5.02	Information availability	-0.812
S9.01	Demand	-0.794
S6.01	Workload	+0.783
S9.02	Information quality	-0.783
S7.01	Variability	+0.743
S13.01	Familiarity	+0.728
S3.01	Familiarity	+0.727
S12.02	Focusing	+0.700
S8.01	Stability	+0.688
S1.01	Attentional load	-0.668
S8.02	Complexity	-0.643
S10.02	Familiarity	+0.585
S4.02	Familiarity	+0.558
S13.04	Information quality	-0.544
S15.02	Predictability	-0.539

TABLE II. LOADINGS ON 2ND PRINCIPAL COMPONENT (VARIANCE: 20.75%)

NO.	CONSTRUCT	LOADING
S9.03	Concentration	+0.874
S1.02	Concentration	+0.753
S2.01	Risk	+0.743
S14.01	Concentration	+0.736
S15.01	Attentional demand	+0.682
S11.03	Information quantity	-0.676
S11.02	Complexity	+0.643
S4.01	Arousal	+0.643
S14.04	Familiarity	+0.641
S12.03	Control	+0.615
S7.02	Concentration	+0.596
S6.04	Arousal	+0.574
S13.01	Familiarity	+0.574
S11.01	Division of attention	-0.570
S3.01	Familiarity	+0.501

TABLE III. LOADINGS ON 3RD PRINCIPAL COMPONENT (VARIANCE: 8.49%)

NO.	CONSTRUCT	LOADING
S14.03	Information quality	-0.821
S7.02	Concentration	-0.556
S15.03	Focusing	-0.547
S5.03	Stability	+0.534
S14.02	Risk	+0.515

TABLE IV. LOADINGS ON 4TH PRINCIPAL COMPONENT (VARIANCE: 6.16%)

NO.	CONSTRUCT	LOADING
S3.02	Consciousness	0.689
S3.04	Motivation	0.578
S13.03	Complexity	-0.554
S8.03	Anticipation	-0.502

TABLE V. SUMMARY OF RATING MEANS (N = 5) AND ANOVA's FOR SET I FLIGHT SCENARIOS

FLIGHT SCENARIO	CONSTRUCTS									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
F1.1	1.2	5.2	4.0	2.0	7.0	6.0	6.6	6.4	2.4	1.8
F1.3	2.6	4.4	3.8	2.4	6.4	5.2	5.6	5.4	2.4	4.0
F1.5	4.6	4.4	3.2	5.2	4.2	2.8	2.8	3.4	3.8	4.8
F1.7	6.8	4.0	4.8	6.4	3.0	2.2	2.2	2.4	6.2	6.2
F1.9	6.6	4.2	5.3	6.8	3.2	1.4	0.7	3.0	4.3	4.8
F1.11	3.6	4.9	2.9	2.8	2.5	2.4	2.8	2.4	1.2	5.0
F1.13	3.2	3.8	5.0	2.0	6.2	3.6	3.4	6.6	5.0	3.6
F1.15	4.0	3.6	4.2	2.4	5.6	4.8	4.8	4.8	5.2	3.0
F1.17	4.2	4.4	4.6	2.6	6.4	6.0	5.8	5.8	4.2	2.8
F2.1	6.6	3.6	6.2	6.6	3.6	2.6	3.0	3.2	6.6	6.4
F2.3	4.4	5.8	5.0	1.0	7.0	7.0	5.8	7.0	4.4	2.8
F2.5	6.4	3.6	4.8	5.0	4.4	3.0	4.2	3.4	5.4	4.8
F2.7	5.8	4.2	4.8	2.8	5.8	4.4	4.6	5.4	4.2	4.0
F2.9	6.6	5.0	5.4	5.4	4.0	3.2	3.4	3.8	6.2	5.2
F2.11	4.6	3.6	4.8	3.4	5.4	3.6	4.8	5.2	3.6	3.6
MEAN	4.74	4.31	4.58	3.79	4.98	3.88	4.04	4.54	4.34	4.18
F RATIO	8.22	0.619	1.753	11.16	7.00	7.02	6.97	6.59	10.91	3.04
PROB.	0.001	NS	NS	0.001	0.001	0.001	0.001	0.001	0.001	0.01

TABLE VI. SUMMARY OF RATING MEANS (N = 5) AND ANOVA's FOR SET II FLIGHT SCENARIOS

FLIGHT SCENARIO	CONSTRUCTS									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
F1.2	4.2	4.4	2.6	2.0	6.4	4.2	3.6	6.0	3.4	4.0
F1,4	5.8	4.4	4.2	5.8	3.0	2.4	2.6	2.2	5.4	5.6
F1.6	4.4	3.8	2.4	1.2	6.8	5.2	3.6	6.6	2.6	2.4
F1.8	7.0	4.4	5.5	6.2	2.4	2.8	2.7	2.4	5.6	6.8
F1.10	3.4	2.4	6.2	3.4	5.8	5.8	5.8	5.4	4.6	3.2
F1.12	2.6	2.0	5.0	2.0	6.8	4.4	4.8	6.2	4.2	1.8
F1.14	4.6	3.6	3.9	3.5	4.6	3.2	4.2	4.8	3.9	3.4
F1.16	5.0	2.6	5.0	3.2	5.8	2.8	2.8	5.4	5.6	3.6
F1.18	3.2	5.2	5.0	2.4	4.4	4.4	5.0	4.2	1.6	3.2
F2.2	5.6	2.8	3.6	3.6	6.0	3.0	3.0	6.2	6.2	4.8
F2.4	4.0	3.2	4.6	2.6	6.6	4.8	4.4	5.4	3.6	2.8
F2.6	4.8	6.0	3.6	6.8	1.4	1.2	1.2	1.2	5.6	6.4
F2.8	5.0	4.6	4.0	2.0	6.6	6.2	5.8	6.0	3.8	3.0
F2.10	5.2	3.2	5.0	4.0	5.8	5.4	4.8	5.4	3.8	3.4
MEAN	4.62	3.75	4.38	3.48	5.17	3.99	3.88	4.81	4.28	3.88
F RATIO	2.02	1.97	2.38	7.57	11.72	5.56	4.42	13.41	4.41	7.62
PROB.	0.05	0.05	0.05	0.001	0.001	0.001	0.001	0.001	0.001	0.001

TABLE VII. CORRELATION MATRIX OF CONSTRUCTS FOR SET I FLIGHT SCENARIOS

NO.	CONSTRUCT	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	Familiarity	1.000									
C2	Focusing	-0.039	1.000								
C3	Info. quantity	0.439	0.002	1.000							
C4	Instability	0.458	-0.207	0.115	1.000						
C5	Concentration	-0.488	0.211	-0.072	-0.793	1.000					
C6	Complexity	-0.373	0.320	-0.088	-0.727	0.766	1.000				
C7	Variability	-0.313	0.355	-0.026	-0.657	0.728	0.811	1.000			
C8	Arousal	-0.402	0.227	0.024	-0.805	0.846	0.757	0.680	1.000		
C9	Info. quality	0.583	-0.182	0.442	0.456	-0.379	-0.394	-0.475	-0.307	1.000	
C10	Spare capacity	0.397	-0.176	0.151	0.674	-0.744	-0.683	-0.765	-0.711	0.472	1.000

TABLE VIII. CORRELATION MATRIX OF CONSTRUCTS FOR SET II FLIGHT SCENARIOS

NO.	CONSTRUCT	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	Familiarity	1.000									
C2	Focusing	0.061	1.000								
C3	Info. quantity	0.077	-0.106	1.000							
C4	Instability	0.253	0.136	0.076	1.000						
C5	Concentration	-0.203	-0.374	-0.027	-0.652	1.000					
C6	Complexity	-0.206	0.109	0.161	-0.558	0.560	1.000				
C7	Variability	-0.297	0.055	0.210	-0.488	0.478	0.858	1.000			
C8	Arousal	-0.285	-0.337	0.048	-0.698	0.817	0.527	0.525	1.000		
C9	Info. quality	0.161	0.046	0.421	0.417	-0.268	-0.356	-0.328	-0.213	1.000	
C10	Spare capacity	0.304	0.114	-0.057	0.615	-0.647	-0.558	-0.591	-0.651	0.322	1.000

TABLE IX. LOADINGS OF CONSTRUCTS ON PRINCIPAL COMPONENTS FOR SET I FLIGHT SCENARIOS

NO.	CONSTRUCT	PRINCIPAL COMPONENTS		
		1st	2nd	3rd
		VAR: 47.89%	VAR: 19.75%	VAR: 11.52%
C1	Familiarity	-0.398	0.728	0.122
C2	Focusing	0.147	-0.016	0.956
C3	Information quantity	0.088	0.859	-0.002
C4	Instability	-0.858	0.206	-0.047
C5	Concentration	0.914	-0.145	0.037
C6	Complexity	0.849	-0.123	0.248
C7	Variability	0.819	-0.113	0.333
C8	Arousal	0.919	-0.026	0.045
C9	Information quality	0.343	0.750	-0.197
C10	Spare capacity	-0.823	-0.225	-0.077

TABLE X. LOADINGS OF CONSTRUCTS ON PRINCIPAL COMPONENTS FOR SET II FLIGHT SCENARIOS

NO.	CONSTRUCT	PRINCIPAL COMPONENTS		
		1st	2nd	3rd
		VAR: 36.52%	VAR: 20.15%	VAR: 15.25%
C1	Familiarity	-0.335	0.142	0.214
C2	Focusing	0.202	0.859	-0.086
C3	Information quantity	0.200	-0.026	0.896
C4	Instability	-0.650	0.434	0.283
C5	Concentration	0.571	-0.688	-0.113
C6	Complexity	0.924	0.002	0.011
C7	Variability	0.915	-0.002	0.063
C8	Arousal	0.607	-0.671	-0.045
C9	Information quality	-0.365	0.046	0.748
C10	Spare capacity	-0.720	0.376	0.103

TABLE XI. SUMMARY OF CONSTRUCT RATING MEANS (N = 24) & ANOVAs FOR PILOT DECISION SCENARIOS

NO.	CONSTRUCT	DECISION SCENARIO						MEAN	F VALUE	PROB <
		P1	P2	P3	P4	P5	P6			
C.1	Attentional demand	5.62	4.15	6.03	5.24	4.13	5.47	5.11	16.60	0.001
C.1.1	Instability	5.50	4.21	5.50	5.00	4.33	5.79	5.05	6.40	0.001
C.1.2	Complexity	5.54	3.71	5.17	4.83	3.92	5.13	4.72	11.36	0.001
C.1.3	Variability	5.88	4.04	5.33	5.04	4.25	5.46	5.00	11.17	0.001
C.2	Attentional supply	5.60	4.66	5.75	4.94	4.70	5.38	5.17	6.52	0.001
C.2.1	Arousal	6.42	4.83	6.46	5.25	4.71	6.08	5.62	22.90	0.001
C.2.2	Concentration	6.21	4.79	6.29	5.17	4.71	5.58	5.46	16.97	0.001
C.2.3	Division	3.96	4.71	3.54	3.92	4.00	3.96	4.01	2.88	0.05
C.2.4	Spare capacity	3.83	5.04	3.13	4.13	4.75	3.67	4.09	10.19	0.001
C.3	Understanding	5.17	5.45	5.00	4.89	4.72	4.28	4.92	3.37	0.01
C.3.1	Information quantity	4.79	5.00	4.75	4.67	4.54	3.83	4.60	3.17	0.05
C.3.2	Information quality	4.25	4.79	4.71	4.33	4.42	4.50	4.50	0.79	NS
C.3.3	Familiarity	4.50	5.58	3.67	5.21	5.38	4.83	4.86	10.14	0.001
C.4	Situation awareness	5.50	5.08	5.46	5.26	4.71	4.61	5.10	2.42	0.05

TABLE XII. SUMMARY OF CONSTRUCT RATING MEANS (N= 19) & ANOVAs FOR NAV DECISION SCENARIOS

NO.	CONSTRUCT	DECISION SCENARIO						MEAN	F VALUE	PROB <
		N1	N2	N3	N4	N5	N6			
C.1	Attentional demand	4.64	5.71	5.64	4.29	5.00	4.57	4.97	3.01	0.05
C.1.1	Instability	4.79	5.63	4.42	5.63	4.50	3.89	4.81	3.01	0.05
C.1.2	Complexity	4.32	5.32	4.79	4.37	3.26	3.32	4.23	5.47	0.001
C.1.3	Variability	4.79	5.68	4.84	5.11	4.00	4.47	4.81	2.81	0.05
C.2	Attentional supply	4.74	5.56	5.68	4.21	5.21	4.66	5.04	4.26	0.01
C.2.1	Arousal	5.26	6.26	6.11	4.95	5.47	5.05	5.52	3.78	0.01
C.2.2	Concentration	4.89	6.32	6.26	4.47	5.42	4.74	5.35	6.96	0.001
C.2.3	Division	4.42	3.16	2.63	4.58	3.89	4.58	3.88	5.14	0.001
C.2.4	Spare capacity	4.37	3.47	2.47	4.58	4.58	4.79	3.99	8.92	0.001
C.3	Understanding	5.57	5.59	5.50	4.28	5.06	5.62	5.27	4.29	0.01
C.3.1	Information quantity	5.32	5.47	4.68	3.84	4.32	5.05	4.78	3.98	0.01
C.3.2	Information quality	5.21	5.32	4.74	3.74	4.68	5.11	4.80	3.64	0.01
C.3.3	Familiarity	5.63	4.42	3.58	5.11	5.11	5.26	4.85	5.50	0.001
C.4	Situational awareness	5.74	5.63	5.84	4.00	4.95	5.00	5.19	4.99	0.001

TABLE XIII. CORRELATION MATRIX OF CONSTRUCTS FOR PILOT DECISION SCENARIOS

NO.	C1	C1.1	C1.2	C1.3	C2	C2.1	C2.2	C2.3	C2.4	C3	C3.1	C3.2	C3.3	C4
C1	1.000													
C1.1	.506	1.000												
C1.2	.675	.561	1.000											
C1.3	.664	.619	.871	1.000										
C2	.601	.346	.430	.452	1.000									
C2.1	.690	.424	.477	.498	.687	1.000								
C2.2	.659	.400	.485	.488	.593	.770	1.000							
C2.3	-.214	-.030	-.077	-.057	-.076	-.055	-.012	1.000						
C2.4	-.612	-.369	-.546	-.446	-.283	-.399	-.383	.444	1.000					
C3	.084	-.161	-.180	-.126	.139	.062	.101	.154	.232	1.000				
C3.1	-.124	-.147	-.260	-.197	-.058	-.084	-.091	.134	.442	.607	1.000			
C3.2	-.173	-.131	-.284	-.269	-.096	-.152	-.191	.178	.337	.426	.638	1.000		
C3.3	-.315	-.182	-.237	-.222	-.012	-.212	-.146	.283	.484	.422	.181	.229	1.000	
C4	.041	.010	-.022	.010	.078	.123	.139	.140	.272	.417	.595	.461	.227	1.000

(R = 0.21 p<0.05; R = 0.27 p<0.01; R = 0.34 p<0.001)

TABLE XIV. CORRELATION MATRIX OF CONSTRUCTS FOR NAVIGATOR DECISION SCENARIOS

NO.	C1	C1.1	C1.2	C1.3	C2	C2.1	C2.2	C2.3	C2.4	C3	C3.1	C3.2	C3.3	C4
C1	1.000													
C1.1	.260	1.000												
C1.2	.541	.333	1.000											
C1.3	.364	.281	.718	1.000										
C2	.532	.078	.191	.223	1.000									
C2.1	.507	.090	.256	.190	.796	1.000								
C2.2	.568	.068	.309	.166	.739	.862	1.000							
C2.3	-.291	.028	-.207	-.165	-.101	-.119	-.200	1.000						
C2.4	-.419	-.182	-.345	-.244	-.190	-.207	-.282	.513	1.000					
C3	.133	.120	.134	.145	.489	.358	.325	.069	.143	1.000				
C3.1	.243	.137	.251	.151	.337	.281	.361	.094	.083	.723	1.000			
C3.2	.202	.078	.073	.051	.462	.358	.333	.055	.088	.682	.634	1.000		
C3.3	-.083	-.123	.049	.227	.090	.047	-.005	.331	.394	.313	.225	.167	1.000	
C4	.497	.042	.266	.116	.649	.585	.566	.080	-.108	.557	.537	.540	.209	1.000

(R = 0.23 p<0.05; R = 0.30 p<0.01; R = 0.38 p<0.001)

TABLE XV. LOADINGS OF CONSTRUCTS ON PRINCIPAL COMPONENTS FOR PILOT DECISION SCENARIOS

NO.	CONSTRUCT	PRINCIPAL COMPONENTS			
		1st	2nd	3rd	4th
		VAR: 22.10%	VAR: 19.69%	VAR: 18.89%	VAR: 12.61%
C.1	Attentional demands	0.686	0.496	-0.019	0.323
C.1.1	Instability	0.217	0.774	0.036	0.030
C.1.2	Complexity	0.354	0.807	0.153	0.104
C.1.3	Variability	0.361	0.830	0.100	0.049
C.2	Attentional supply	0.826	0.178	0.002	-0.017
C.2.1	Arousal	0.825	0.299	0.000	0.101
C.2.2	Concentration	0.809	0.295	0.017	0.029
C.2.3	Division	-0.098	0.138	-0.077	-0.820
C.2.4	Spare capacity	-0.346	-0.350	-0.316	-0.635
C.3	Understanding	0.346	-0.297	-0.658	-0.211
C.3.1	Information quantity	-0.063	-0.120	-0.896	-0.068
C.3.2	Information quality	-0.183	-0.093	-0.795	-0.073
C.3.3	Familiarity	0.071	-0.313	-0.176	-0.696
C.4	Situation awareness	0.102	0.106	-0.778	-0.147

TABLE XVI. LOADINGS OF CONSTRUCTS ON PRINCIPAL COMPONENTS FOR NAVIGATOR DECISION SCENARIOS

NO.	CONSTRUCT	PRINCIPAL COMPONENTS			
		1st	2nd	3rd	4th
		VAR: 24.48%	VAR: 18.77%	VAR: 16.27%	VAR: 13.34%
C.1	Attentional demands	-0.591	-0.092	0.484	0.285
C.1.1	Instability	0.179	-0.320	0.508	0.293
C.1.2	Complexity	-0.186	-0.079	0.874	0.090
C.1.3	Variability	-0.114	0.000	0.885	-0.114
C.2	Attentional supply	-0.845	-0.289	0.085	0.002
C.2.1	Arousal	-0.894	-0.157	0.097	0.024
C.2.2	Concentration	-0.878	-0.167	0.118	0.122
C.2.3	Division	0.188	-0.155	-0.158	-0.651
C.2.4	Spare capacity	0.263	-0.160	-0.327	-0.695
C.3	Understanding	-0.256	-0.833	0.053	-0.181
C.3.1	Information quantity	-0.184	-0.838	0.144	-0.092
C.3.2	Information quality	-0.278	-0.815	-0.059	-0.036
C.3.3	Familiarity	-0.080	-0.120	0.196	-0.838
C.4	Situation awareness	-0.652	-0.501	0.097	-0.113

PERFORMANCE-BASED MEASURES OF MERIT FOR TACTICAL SITUATION AWARENESS

by

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SUMMARY

Pilot situation awareness is not a well-understood concept. Most attempts at understanding situation awareness have relied almost exclusively on subjective reports, and have not led to a clear understanding of the concept. The present work represents a performance-based approach to assessing situation awareness, where the relationship between pilot-reported situation awareness and tactical task performance is investigated. Aspects of a high-realism air combat simulation were analyzed in terms of a priori hypotheses regarding performance of a tactical task (fire point selection), its relation to pilot-reported situation awareness, and its relation with mission outcome. Results showed that pilot-reported situation awareness by itself was not a reliable indicator of pilot performance (based on mission outcome). Further, pilot performance by itself was not systematically related to fire point selection. Only when the simultaneous operation of pilot performance, fire point selection, and pilot-reported situation awareness are considered does a systematic relationship emerge. The highest mission performance scores were associated with <u>both</u> a FPS within a preferred zone (80-100% RMAX2) <u>and</u> high pilot-reported SA ratings. Lower performance scores were observed as pilots' FPS diverged from the preferred FPS area and reported lower SA scores. The drop-off in mission performance is more severe when pilots launched their weapons inside the 80-100% RMAX2 area relative to launching outside this preferred area. These findings are interpreted in terms of fire point selection as one potential measure of merit for tactical situation awareness.

INTRODUCTION

To date, pilot situation awareness (SA) has been an amorphous concept whose interactions and influence on pilot task performance is largely undefined. One approach to lending structure to defining SA measures is to determine the information elements the pilot uses to develop an adequate "state of knowing" relative to specific tactical tasks, and to determine measures for pilot "states of doing" that optimize overall mission performance. Current studies have focused on the cognitive models, paradigms, and mental states of the pilot as he proceeds through a mission. At best, these studies loosely define pilot SA level as a stand alone value based on recall or workload. None of the studies relate SA level with pilot performance in measurable terms. Given that a "state of knowing" and proper task execution based on that knowledge state are essential elements for successful mission performance, measures of merit for situation awareness must include both subjective and objective task performance measures to adequately assess SA.

The purpose of this paper is to report the development of measures of merit for pilot situation awareness by defining measurable relationships between the tactical pilot's reported "state of knowing" and his "state of doing" for specific air combat tasks. This relationship is reflected in the pilot's overall performance based on mission goals. The methodology presented here reflects an embedded task technique for determining situation awareness. Variations in some knowledge state (i.e., situation awareness) are inferred from variations in a measured objective performance (i.e., a tactical air combat task).

In order to support the analysis of a knowledge state/performance relationship, a data base for a representative air combat simulation was selected which contained task-based data, mission outcome data, and subjective SA data. This simulation was the Advanced Medium-Range Air-to-Air Missile Operational Utility Evaluation test (AMRAAM OUE) test conducted in 1981-82. Specific hypotheses were formed relative to five critical tactical air combat task areas. These five tactical task areas were identified based upon the results of a previous determination of critical tactical tasks. These tasks were 1) fire point selection (FPS), which is that relative spatial position where the pilot decides to fire his weapons (air-to-air missile); 2) weapons envelope management, which is energy maneuverability and P_s (specific excess energy) in relationship to achieving weapons launch parameters; 3) target sort and selection, which is the identification and prioritization of targets based primarily on information from onboard sensors; 4) defensive/counter-offensive maneuver, which is the pilot response to threat actions or attack; and 5) mutual support of formations, which is the complex relationship among flight elements to provide synergistic enhancement of offensive firepower and survivability. This paper presents results from the fire point selection analysis only. The core of these results involve a description of the complex relationships that were found between mission outcome, self-reported pilot situation awareness level, and fire point selection.

A number of relationships were predicted in the analysis of the relationships among SA, FPS, and mission performance. First, it was hypothesized that pilot SA level would be positively correlated with mission performance. Second, it was predicted that mission performance levels would be influenced by fire point selection within the missile launch envelope. Third, it was expected that the most accurate predictions of good and poor mission performance would be obtained through consideration of the joint operation of fire point selection and pilot SA level.

METHOD

Subjects

Sixteen tactical pilots participated in the original AMRAAM Operational Utility Evaluation simulation. Eight pilots were experienced F-15 pilots and eight were experienced F-16 pilots.

Measures

Pilot Performance Index. The only mission outcome data calculated during the original AMRAAM test were mission scores for the overall flight. In order to evaluate relationships between individual pilot task performance and pilot SA levels, an index more sensitive to individual performance was developed and used. Mission outcome was measured by the Pilot Performance Index (PPI), which was a weighted score based on the ratio of the number of adversary aircraft "killed" to the number of friendly losses. The PPI values ranged from -443 to 1196. Values less than zero were classified as poor mission performance, while values ranging from 0-299 were considered as average performance, and values greater than 299 were classified as good mission performance.

Reported SA measure. The pilot-reported SA data consisted of subjective ratings collected at the time of the simulation, and were obtained from three sources. After each trial, the pilot rated his own SA level, the flight lead rated the overall flight SA level, and a trained observer (a qualified tactical pilot) also rated the overall flight SA level. These ratings were based on planned tactics, executed tactics, an assessment of the flight's response to tactical situations, and the participants' awareness of on-going tactical events, independent of the final engagement outcome. A fourth SA rating was derived, which was the average of individual pilot SA ratings for each flight.

Fire Point Selection. Task-based data collected on fire point selection included actual missile launch range, no escape range, aspect at launch, and minimum and maximum range data for all AMRAAM launches. The FPS values used in the present analyses were expressed as a percentage of RMAX2, which was calculated by dividing the actual launch range by the no escape range (no escape range may be conceptualized here as the minimum range at which a target could execute a successful evasive maneuver to defeat a missile). The percentage of RMAX2 values used in this study were approximately equivalent to no escape range for the AMRAAM.

A total of 48 trials (24 F-15 and 24 F-16) were used in the analysis.

RESULTS AND DISCUSSION

Three relationships were investigated using self-reported SA and Pilot Performance Index data. First, the extent of the relationship between pilot-reported SA and Pilot Performance Index was examined to evaluate mission performance sensitivity to self-reported SA level. Second, the Fire Point Selection and Pilot Performance Index relationship was evaluated to establish mission performance sensitivity to specific task execution, which, in this case, was FPS. Third, mission performance was evaluated as a joint function of FPS and pilot-reported SA.

Reported SA and mission performance. Correlations were computed to determine the relationship between self-reported SA levels and mission performance (PPI). The pilot-reported SA relationship with PPI was moderate (r = .55 for F-15 trials; r = .60 for F-16 trials). The observer-reported SA relationship with the flight composite PPI (overall flight performance) was also quite strong (r = .68 for F-15 trials; r = .85 for F-16 trials). The relationship between pilot-reported SA and individual pilot PPI was examined more closely by categorizing pilot-reported SA and PPI into three categories: good, average, and poor. The distribution of SA ratings as a function of PPI is presented in Table 1. Based on these data, three observations may be made. First, those pilots who rated their SA as poor also had low PPI scores, reflecting poor performance. Second, those pilots rated their SA as average had average PPI scores. Third, and most importantly, for those pilots who rated their SA as good, a subset had superior PPI scores, while another subset had average or low PPI scores. It appears that

Table 1. The distribution of SA ratings as a function of PPI.

	F-15			F-16		
	Pilot Performance Index (PPI)					
	Good	Average	Poor	Good	Average	Poor
SA Rating						
Good	27	6	13	20	14	10
Average	0	5	7	0	3	5
Poor	0	0	4	0	0	5

subjectively-reported SA may not be an accurate predictor of good mission performance. Good SA, as rated by the pilot, appears to be a necessary but not sufficient contributor to good pilot performance.

FPS and mission performance. Three missile firing regions were identified: 1) a preferred region where most of the pilots launched missiles (80-100% RMAX2 for the nose and front quarter aspects, and 60-70% RMAX2 for the beam aspect); 2) a secondary region where most of the remaining pilots launched (100-130% RMAX2); and 3) a transition region. Note that the term "preferred" used here refers to observed pilot FPS and does not necessarily imply an optimum FPS. The highest PPI scores were in the preferred region for the nose and front quarter aspects. For the beam aspect, which is indicative of later stages of an air combat engagement where the participants are closer in range, the highest PPI scores were in both the transition and preferred regions. Average mission performance scores were found in the secondary FPS region. It is of significant interest that the poorest scores were found in the preferred region, indicating that FPS, by itself, is not an indicator of good mission performance. To obtain information concerning the overall distribution of scores by FPS area, individual PPI scores were summed for all trials and plotted as a function of FPS. These data are shown in Figure 1, which shows that mission performance is highest within the 80-100% RMAX2 region. Mission performance values are lower at closer FPS values (e.g., inside the 80-100% RMAX2 area) relative to FPS values beyond this preferred area.

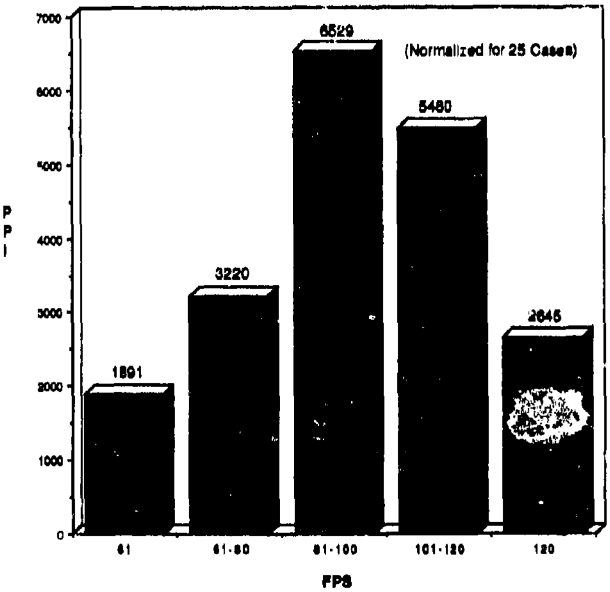

Figure 1. Mission performance (PPI) as a function of fire point selection area.

A number of statements summarize the FPS-performance relationship. First, launching within the 80-100% RMAX2 area may lead to high mission performance, but does not guarantee it. Second, launching within the secondary FPS region reduces the opportunity to achieve high mission performance, but increases survivability. Third, launching outside the preferred and secondary FPS regions leads to poor mission performance.

FPS, Reported SA, and mission performance. It was expected that the most accurate predictions of good and poor mission performance would be obtained through consideration of the joint operation of fire point selection and pilot-reported SA level. The relationships among PPI, FPS, and pilot-reported SA are presented in three-dimensional space in Figure 2. Each set of points represents one participating pilot's FPS values averaged over aspect geometry. Data points represented by cubes are those pilots who have high PPI and who also reported high SA levels. Points represented by pyramids are those pilots who have average PPI levels, and who reported average SA levels. Inverted pyramids represent pilots who had low PPI scores and who reported low SA levels. Finally, the black balls represent pilots who obtained average to low PPI scores, but who reported high SA levels. It can be

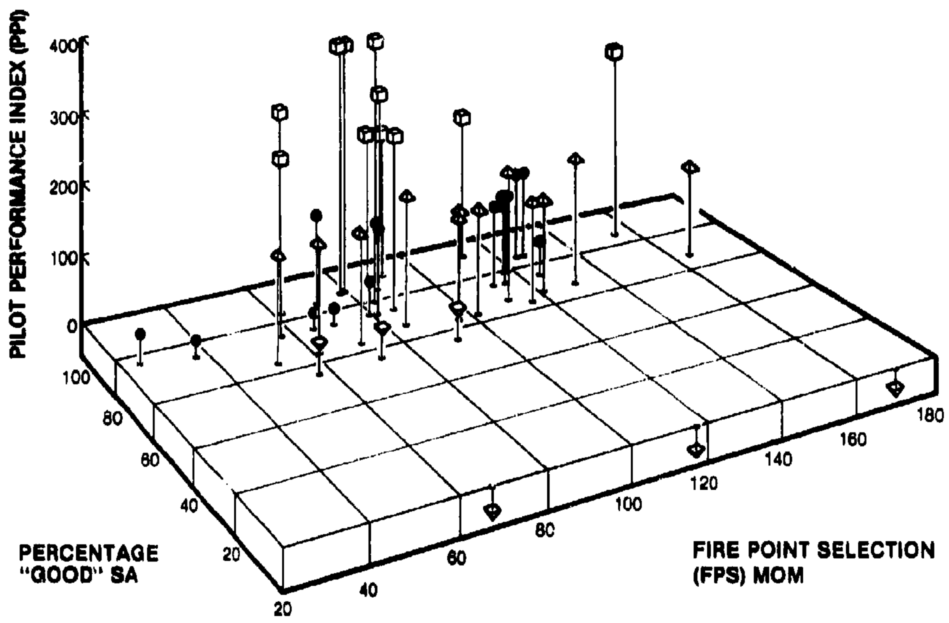

Figure 2. Mission performance (PPI) as a function of fire point selection area (expressed as a percentage of RMAX2) and reported situation awareness level.

seen, in Figure 2, that the highest PPI scores were associated with both a FPS within the 80-100% RMAX2 region and high SA rankings. Lower performance scores were observed as pilots' FPS diverged from the 80-100% RMAX2 area and reported lower SA scores. It can also be seen that the drop-off in performance is more severe when pilots launched their weapons inside the 80-100% RMAX2 area relative to launching outside this preferred area. Consideration of the relationship of all three variables allows an explanation of variability of PPI values within the preferred FPS region. The SA ratings of individual pilots allows a rank ordering of pilots' PPI values within the 80-100% RMAX2 region: as pilot SA increases, performance also increases. Neither high SA or proper FPS by themselves predict the highest performance; it is their combination that produces optimal mission performance.

It was observed that some pilots tended to overrate their SA level relative to their mission performance. In order to investigate this further, pilot PPI scores were rank ordered and compared with their respective self-reported SA ratings. This ranking allowed the separation of pilots into two groups: 1) pilots whose self-reported SA scores reflected actual mission performance as it varied from high to low; and 2) pilots whose self-reported SA scores did not correspond with their overall mission performance. As can be seen by the black balls in Figure 2, pilots whose self-reported SA levels were not representative of their performance tended to launch outside the 80-100% RMAX2 area, resulting in lower PPI values. These pilots tended to deviate from the preferred FPS area for nose, front quarter, and beam aspects. It is possible that erratic and inconsistent FPS patterns were evidence of a lack of an accurate internal representation of the air battle. This incomplete or inaccurate "state of knowing" forced pilots to enter a "state of doing" that was less than optimal, and possibly even random in some cases, which resulted in poor mission performance. On the other hand, pilots who reported high SA levels and launched weapons in the preferred FPS region had built an accurate mental representation of the air battle, and actively searched for and found consistent and controlled FPS launch patterns.

Two statements summarize the relationships among FPS, pilot-reported SA, and mission performance. First, launching within the 80-100% RMAX2 area may lead to high mission performance when accompanied by reported high SA levels. Second, launching at extreme or erratic FPS values may be an indicator of poor situation awareness.

There appears to be a relationship between FPS and mission outcome that indicated evidence of aspect-dependent optimum FPS areas. Launching weapons within these zones, on the average, produced higher performance than launching outside these zones. Launching inside these zones reduces performance dramatically because the increase in P_K is overridden by the decrease in P_S. Firing outside these zones also reduces performance, but the effect is less pronounced since this performance decrease is primarily due to decreasing P_K. Experienced fighter pilots know that these FPS zones exist, but several information elements must be provided to the pilot in a coherent format before he can make practical use of this knowledge. These information elements are task-specific rather than global in nature, and are often inferred (based on air combat training experience). Such information elements include relative spatial positions, changes in these relative spatial positions, closure rates, ownship weapons envelopes, target aspect angles, estimated enemy weapons envelopes, perceived enemy tactics. These are the knowledge elements that in part comprise situation awareness. Typically, these information elements come from several displays as well as the pilot's own senses. The information must then be interpreted by the pilot and integrated into his rapidly-changing representation of the air combat environment. Unfortunately, present displays do not afford easy and efficient integration for the pilot, which in turn makes it difficult to achieve satisfactory situation awareness. For example, in a beyond-visual-range engagement the only indication a pilot has of an abrupt adversary counter-maneuver may be a rapid decrease in indicated closure rate. The pilot is then forced to obtain information on the adversary's aspect angle from another display, and integrate that data element with information from other displays to determine rapidly changing geometries.

Definable relationships appear to exist between pilot-reported SA level, task execution, and overall performance based on the trials selected from the AMRAAM OUE simulation. This data base had several limitations that affected the accuracy of SA measurements. Due to these problems, the exact nature of the complex SA-performance relationships could not be rigorously assessed. These results, however, provide a basis for structuring data base organization and data collection elements in future high-realism simulations of air combat.

APPLICATIONS

The methodologies and results described have applications to design areas that include the development of tactical displays, artificial intelligence applications for fighter aircraft, and development of cockpit automation concepts.

As an example, it is interesting to note that in the AMRAAM OUE simulation, RMAX2 was displayed in standard F-15/F-16 heads-up display (HUD) and in vertical situation display (VSD) formats. However, the pilots chose very different FPS patterns, indicating that the displayed information was used differently, or in some cases may not have been used at all. From the perspective of tactical display design for the cockpit, it is crucial to develop display formats that allow quick and accurate extraction of relationships among elements related to situation awareness. Portrayal of these relationships are influential in determining effective execution of tactical tasks such as fire point selection. A specific example of a potential display format that indicates information relationships relevant to fire point display is shown in Figure 3. One candidate SA display format is shown on the left, while an alternative display format including FPS relationships is shown on the right. In these display formats, own aircraft is represented by the arrow at the bottom center of each display. The other three arrows represent adversary aircraft at different aspect angles and different ranges. In the display showing FPS relationships, the launch envelopes are referenced to two in-range targets versus own aircraft. (Note the difference in launch envelope shapes for the nose-on and beam aspects, reflecting the effects of geometry). The shape of the envelope attached to each target aircraft reflects a possible preferred and secondary FPS regions, giving the pilot an accurate and usable representation of launch options. The target beyond maximum range has no envelope. This example of an FPS-based display provides the pilot with relationships that map more closely with the pilot's mental representation of geometries inherent in air combat, allowing greater correspondence between the display format and the mental model of the dynamic situation.

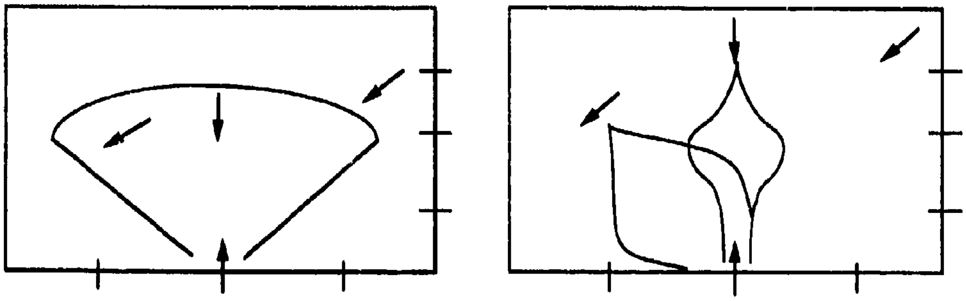

Figure 3. Possible Situation Awareness displays showing missile launch envelopes.
Typical "fan" display is on left; FPS-based display is on right.

EVALUATION OF THE SITUATIONAL AWARENESS RATING TECHNIQUE (SART) AS A TOOL FOR AIRCREW SYSTEMS DESIGN

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SUMMARY

The Situational Awareness Rating Technique (SART) has been developed as an evaluation tool for aircrew systems design. SART provides subjective estimates of attentional Demand and Supply, and ratings of Understanding, which are postulated to be the three primary components of situational awareness. Whilst consistent with contemporary theories of cognition, the application of SART requires knowledge of performance. SART sensitivity seems likely to depend on the contribution of skill, rule, and knowledge-based behaviour, and on the role of explicit and implicit knowledge in the candidate task situation. This paper reports an evaluation of SART in three aircrew systems design studies with different task requirements : (1) Multiple Task Compatibility Study, (2) Attitude Recovery/Attention-Switching Study, (3) Warnings Comprehension Study. SART Demand, Supply, and Understanding ratings showed significant effects of experimental manipulations in all three studies. The relevance of the specific SART components was related to the contribution of skill, rule, and knowledge-based behaviour to the tasks. The SART ratings also highlighted weaknesses in the performance measures and improved their interpretation. Thus, in combination with performance measures, SART provides a powerful tool for aircrew system design.

INTRODUCTION

As Situational Awareness (SA) has become recognised as a major design objective, many attempts have been made to provide a working definition of it. These definitions, which have proved almost as numerous as the authors making them, these are listed by Fracker [1]. They all contain, however, common elements. These are 'knowledge of the pilot'; 'understanding of goals';and 'tactical awareness'. They tend to ignore considerations of workload, which tend to be treated as independent of SA. Fracker's description of SA is in terms of the knowledge structures of the pilot or his 'schemata' [2]. The more applicable and accurate these schemata are, then the better the pilot's assessment of the particular situation and hence the better his SA. This is mediated by the working memory limits of the pilot i.e. insufficient spare working memory will interfere with schemata being called up from long-term memory, thus resulting in reduced capacity for situation assessment and reduced SA.

The approach taken by Fracker is an essentially theoretical one, with empirical testing of it as a consequence rather than an antecedent. An alternative approach to the definition of SA was taken by Taylor [3,4]. He used Personal Construct Theory [5] as a method of eliciting knowledge from aircrew about the factors affecting SA. Thus this approach used no a priori definition of SA, but elicited that definition empirically from the knowledge and experience of aircrew. Taylor found that ten independent bipolar constructs or 'dimensions' emerged. These he formed into a ten dimensional (10-D) Situational Awareness Rating Technique (SART) shown in Figure 1 (below). Further analysis of the 10-D scale results indicated that there were three major groupings or 'domains' within the ten constructs. He classified these under the headings of Demand on Attentional Resources; Supply of Attentional Resources; and Understanding. The 10-D constructs within each of these three domains are indicated in Figure 1. These generic groupings were formed into the three dimensional (3-D) version of the SART scale shown in Figure 2 (below).

The advantage of SART is that, since the dimensions were elicited from the knowledge of aircrew, then they are likely to have high ecological validity. This is likely to be beneficial in applying the scale in the design of aircrew systems, particularly in comparison to more theoretically derived approaches to SA measurement. Further, since the scale takes account of both demand and supply of attentional resources, it should provide some measure of how differing workload will affect SA, as well as how the more 'knowledge-based' measures apply. What is unclear from the previous SART work is the accuracy of the scale in the complex, dynamic situations facing aircrew and the degree of 'diagnosticity' or predictive value that it will have in the real-world.

This paper describes three experiments which were conducted to try to evaluate the utility of SART as a tool for aircrew systems design, both in terms of its accuracy and its diagnosticity. Rasmussen [6] provided a taxonomy of task performance in terms of three types of behaviour. These he called Skill-based i.e. manual/visuo-spatial tasks requiring little application of either rules (algorithms) or knowledge (heuristics); Rule-based i.e. where algorithmic computation of information is required to perform the task by means of defined rules; and Knowledge-based i.e. where existing knowledge must be applied heuristically to perform the task. This taxonomy was used across the three experiments to attempt to test the SART scales with the three types of task, in an attempt to show that any utility of SART will be generalisable across the variety of tasks faced by aircrew. The three studies also use performance testing, in addition to

SART ratings. Although a full report of the performance measures obtained is beyond the scope of this paper, a comparison of performance data and SART data is used to investigate whether the scale can be a useful predictor of operator performance and the degree to which it is sensitive to design variation. The studies also attempt to ascertain the utility of the 3-D SART scale as a low-intrusiveness alternative to the original 10-D scale. The length of the 10-D SART might prohibit it from some airborne applications because of interference with the fight task. Thus the shorter 3-D SART may be more applicable to in-flight testing. These studies, therefore, attempt to investigate whether the same generic constructs would emerge from the 10-D scale and if so, whether an administration using the generic constructs only would have sufficient diagnosticity to justify its administration in place of the 10-D scale where intrusiveness is a primary consideration.

SART

Figure 1 (below) shows the 10-Dimensional (10-D) SART scale. It contains the ten unipolar constructs described by Taylor. Each is rated on a seven-point scale from LOW (1) to HIGH (7).

FIGURE 1. 10-DIMENSIONAL SART SCALE

		LOW						HIGH
		1	2	3	4	5	6	7
DEMAND	INSTABILITY OF SITUATION							
	VARIABILITY OF SITUATION							
	COMPLEXITY OF SITUATION							
SUPPLY	AROUSAL							
	SPARE MENTAL CAPACITY							
	CONCENTRATION							
	DIVISION OF ATTENTION							
UNDERS.	INFORMATION QUANTITY							
	INFORMATION QUALITY							
	FAMILIARITY							

Figure 2 (below) shows the 3-Dimensional SART scale. It contains the three generic constructs derived by SART, plus a fourth rating of subjective situational awareness. Each construct is rated by marking a continuous 100 millimetre line from LOW (0 mm) to HIGH (100 mm).

FIGURE 2. 3-DIMENSIONAL SART SCALE

Demand on Attentional Resources

LOW HIGH

Supply of Attentional Resources

LOW HIGH

Understanding

LOW HIGH

Situational Awareness

LOW HIGH

An administration of the SART scale using a combined 10-D and 3-D scale was also used. This was similar to the 10-D administration with the inclusion of the four generic constructs shown in Figure 2 and used the seven-point rating scale shown in Figure 1.

STUDY 1 - MULTIPLE-TASK COMPATIBILITY STUDY

INTRODUCTION

This study investigated the compatibility of left/right hemisphere-specific tasks in competition for attentional resources. Wickens et al [7] showed that dual-task performance was improved when information was given direct access to that hemisphere dealing with its processing. For 'right-handers' there will be a benefit when visuo-spatial information is displayed to the left visual field (and hence to the right cerebral hemisphere), with the opposite being true for verbal information. This finding has potential implications for the allocation of information on Head Up Displays (HUDs). This study used a simulated HUD to investigate whether, with a central (i.e. left and right visual field) tracking task, there was a benefit in displaying additional peripheral information according to the Wickens et al model. The experimental tasks were essentially Skill-based calling on both manual tracking and attention-switching skills. It was also hoped to show that the SART scale would be sensitive to the differences in attentional demand induced by the experimental variables.

METHOD

Subjects were required to perform combinations of four experimental tasks. The first was to monitor the random movement of a pointer against a fixed vertical scale, and to respond when the pointer reached the upper or lower scale limit. The visual field to which the pointer task was presented was varied. The second task was to maintain the position of an aircraft reference symbol in relation to a pitch bar. The pitch scale movement simulated deviations in both roll and pitch. This tracking task occurred in the centre of the S's visual field. The third task was a short-term memory task [8]. Subjects were presented with a series of seven single digits, displayed in the centre of the aircraft reference symbol. Subjects were asked to read the digits aloud, as they were presented, and to report whether a subsequent digit (presented after a two second delay) had occurred during the initial seven. The fourth task was used as an alternative to the memory task only. This was a simple vigilance task. Subjects were required to monitor the centre of the aircraft reference symbol and to respond when a target (the letter X) was presented. The pointer task was taken as the primary task, and was carried out with and without the concurrent tracking and memory/vigilance tasks to provide the variation in task workload. The number of correct identifications made on the pointer task was taken as the main performance measure. The combined 10-D/3-D SART administration was used.

RESULTS

TABLE 1. VARIMAX ROTATED FACTORS OBTAINED FROM THE COMBINED 10-D/3-D SART

	FAC.1	FAC.2	FAC.3	FAC.4
DEMAND	0.88	-0.03	0.10	-0.10
INSTABILITY	0.79	-0.04	0.27	0.01
COMPLEXITY	0.88	-0.09	0.17	0.02
VARIABILITY	0.81	0.08	0.32	0.05
SUPPLY	0.59	-0.08	0.54	-0.23
AROUSAL	0.34	0.05	0.80	-0.14
CONCENTRATION	0.27	0.01	0.83	-0.05
DIVISION OF ATTENTION	0.23	0.07	0.62	-0.04
SPARE MENTAL CAPACITY	-0.55	0.50	-0.13	-0.18
UNDERSTANDING	-0.01	0.57	-0.32	-0.44
INFORMATION QUANTITY	0.06	0.86	-0.14	-0.01
INFORMATION QUALITY	-0.04	0.82	0.27	-0.06
FAMILIARITY	-0.26	0.61	0.19	-0.07
SITUATIONAL AWARENESS	0.02	0.09	0.18	-0.88

A Principal Components analysis, using Varimax rotation, was performed on the scores obtained from the combined 10-D/3-D SART The results are shown in Table 1 (above). Four factors were found, which accounted for over 75% of the total variance. The first factor weighted highly on the generic 'Demand on Attentional Resources' plus the three original dimensions which had been grouped to produce that construct. This factor accounted for the largest proportion of the total variance. This is in line with the predictions of the study where demand was the main experimental variable. The second factor weighted highly on the generic 'Understanding' construct plus the three original dimensions grouped within it. The third factor weighted highly on 'Supply of Attentional Resources' plus three of the four dimensions grouped within it. The exception was 'Spare Mental Capacity' which appeared more linked to Demand and Understanding in this study. The fourth factor, which accounted for only a small proportion of the total variance, weighted highly on the 'Situational Awareness' construct. Thus the factors emerging appear to be in line with those found by Taylor, with the only deviation being for Spare Mental Capacity. Situational Awareness, as a construct, accounted for little variance and showed only weak links with the other constructs.

The primary performance measure (Pointer task) showed significant differences across the experimental conditions. The number of 'Hits' scored on this task was significantly reduced by the addition of the Tracking task ($p<0.001$) and the Memory task ($p<0.001$). It also showed a significant Memory by Tracking interaction ($p<0.001$) with scores showing the largest decrement where the two additional tasks were required concurrently. The implication of these results is that the Pointer task was sensitive to increases in workload, with scores being reduced as additional sources of workload were imposed.

ANOVAs were carried out on the factors obtained by the Principal Components analysis to determine the sensitivity of the factors to the increases in workload across conditions. Factor 1,which corresponded to the Demand constructs, showed a significant increase with the addition of the Memory task ($p<0.001$) and the Tracking task ($p<0.001$). There was also a significant Memory by Tracking interaction ($p<0.01$). This provides further evidence that this factor provided a measure of the demands of the tasks since it showed the same pattern as the primary performance measure. Factor 2, corresponding to Understanding, showed a significant effect ($p<0.001$) of the presence of the Memory task only. Scores on Factor 2 were lower during the Memory task. Since the Memory task was the only Rule-based task used, this supports the idea that Factor 2 is measuring Understanding, since it is understanding that is likely to be sensitive to changes in rule-based behaviour. Factor 3, corresponding to Supply, showed an increase ($p<0.05$) in scores when the Tracking task was present. This is a smaller effect but may imply that supply of attention was being increased to cope with the continuous Tracking task. There were no significant effects of Factor 4.

DISCUSSION

The results of this study provide good support for the internal SART structure suggested by Taylor. The three generic constructs of Demand, Supply, and Understanding and their associated dimension groupings appear to re-emerge in this study. The only exception to this is Spare Mental Capacity which no longer appears to lie within the supply construct grouping. It is unclear from this study, however, whether this dissociation is an artifact of the design or a genuine effect. A comparison of the performance and the SART data shows that both appear to have sensitivity to the design variables. They provide a further indication of the validity of the generic groupings, since the factor scores obtained are consistent with the a priori predictions within the experiment. Demand was sensitive to the increase in the number of tasks subjects were required to perform. Understanding was sensitive to the inclusion of a more rule-based or 'cognitive' task. Supply appeared to be sensitive to the inclusion of a continuous rather than discrete task. The lack of diagnostic power of the fourth factor, which appeared to represent the unidimensional Situational Awareness rating, can be taken as further evidence of the need for a multidimensional scale to represent accurately a concept as complex as SA.

STUDY 2 - ATTITUDE RECOVERY/ATTENTION-SWITCHING

INTRODUCTION

This study investigated whether there were penalties during attitude recovery caused by the need to switch attention between more than one type of attitude reference. Where the HUD is being used as the primary flight instrument, penalties may occur in switching from the HUD attitude reference system to a conventional Attitude Indicator (AI) within the cockpit and vice versa. Such difficulties may occur if having to switch attention rapidly between the two, as during emergency attitude recovery, results in the operator having an inappropriate mental model or schema in his working memory. This may lead to a delay occurring before he can proceed with understanding the attitude representation, whilst the appropriate schema is being selected. Such delays may suggest that a common representation should be available both Head-Up and Head-Down. This study used an attitude recovery paradigm to investigate this effect. Three types of attitude reference were used. The first was a canted pitch bar HUD scale.The second was a simulated computer graphics AI ball. The third was a pictorial 'Follow Me' Command Indicator (CI). This was in the form of a line-astern view of a 'buddy' aircraft which, if followed, would guide one's own aircraft back to the desired attitude [9,10].

METHOD

Eighteen aircrew subjects were tested. All subjects were student pilots receiving combat training and were of similar age and flying experience. All subjects had experience of AI symbology but were naive to HUD symbology. Pairs of static attitude representations were presented tachistoscopically to subjects, with a two second interval between the first and second presentations. The first attitude was presented as the Desired Attitude. Subjects were required to hold this in memory until presentation of the second attitude, designated the Actual Attitude. Subjects were required to make the appropriate input (via a joystick) to recover from the Actual attitude to the Desired attitude. Desired attitude was represented using either the HUD or the AI attitude reference system. Actual Attitude was presented either using the HUD or AI systems or by the 'Follow Me' Command Indicator. Where the CI was presented, subjects did not needto calculate relative differences between Actual and Desired attitudes, but merely to make the control input necessary to follow the displayed aircraft. Six conditions were given to each subject i.e. both initial reference systems with each of the three types of secondary representations. There were eight trials per condition. In order to study the rule-based aspects of the task only, subjects were required to only make the initial input towards the recovery rather than to complete the series of control inputs needed to make a full recovery. This was since, to be able to make the initial input, understanding of the attitude differential must have been gained and the relevant mental rules for recovery instigated. Subjects were required to complete a 3-D SART scale after each trial (pair of attitudes) and a 10-D SART after completion of each condition.

RESULTS

TABLE 2. VARIMAX ROTATED FACTORS OBTAINED FROM THE 10-D SART

	FAC.1	FAC.2	FAC.3
INSTABILITY	0.05	0.75	-0.24
COMPLEXITY	0.20	0.86	0.05
VARIABILITY	0.15	0.89	-0.12
AROUSAL	0.01	0.15	-0.76
CONCENTRATION	-0.56	0.12	-0.41
DIVISION OF ATTENTION	-0.37	0.13	-0.62
SPARE MENTAL CAPACITY	-0.22	-0.53	-0.44
INFORMATION QUANTITY	-0.82	-0.24	-0.17
INFORMATION QUALITY	-0.78	-0.10	-0.26
FAMILIARITY	-0.72	-0.10	0.19

A Principal Components analysis on the data from the 10-D SART produced three factors which are shown in Table 2 (above). The highest weightings on Factor 1 are for Information Quantity, Information Quality, and Familiarity. This is the same grouping found by Taylor within his generic Understanding construct. The highest weightings on Factor 2 are for Instability, Complexity, and Variability. This again corresponds with the grouping found for Demand on Attentional Resources. The highest weightings on Factor 3 are for Arousal, Concentration, Division of attention, and Spare Mental Capacity. This in turn corresponds to the original grouping found for Supply of Attentional Resources. This pattern is further confirmed by the greatest amount of total variance being accounted for by the understanding dimensions, which is what would be predicted for a predominantly rule-based task.

ANOVAs were performed on the three factors derived from the 10-D S.A.R.T and on the scores from the 3-D SART to test their sensitivity to the experimental conditions. Factor 1 (Understanding) was found to differ significantly across the representations used for both the first and second attitudes. Factor 1 scores were lower overall when the HUD was shown first (p(0.01). This is probably due to the subjects' inexperience with the HUD pitch scale reducing their understanding of it. Factor 1 scores were also significantly lower (p(0.05) when the HUD was presented second than when the AI was presented second. Again this would imply a reduced understanding of the symbology in the HUD representation, which was unfamiliar, as compared to the much more familiar AI symbology. Scores for the CI condition fell between the two other conditions. High understanding was not expected with the CI since it did not require the same depth of understanding to complete the task. An ANOVA on scores from the 3-D Understanding rating showed a similar pattern of results with significant differences between attitude reference systems on both the first (p(0.01) and second (p(0.001) representations. In both cases the HUD provided reduced understanding.

Factor 2 (Demand) showed a significant difference between the attitude representations presented second. The HUD produced the highest scores while the CI produced the lowest (p(0.001). The HUD symbology would be expected to require higher mental workload to use than the AI since it was a unfamiliar to the subjects. The CI would be expected to cause the least workload since it did not require computation of relative attitude differences, as with the other representations, but merely a control input to achieve an attitude relative to the pilot's egocentric position. For the 3-D Demand scores, a similar pattern was seen with differences occurring only between the second types of attitude reference. Again the HUD was found to produce the highest demand and the CI the lowest (p 0.001). Neither Factor 3 nor the 3-D Supply construct detected any significant differences.

These results are consistent with the performance data, where conditions in which the second presentation used the HUD symbology produced longer response latencies (p(0.01) than those using the AI symbology. The shortest response times were produced by the CI conditions.

DISCUSSION

It appears that the reduced understanding (and consequently higher workload) produced by the HUD symbology affected the time needed to begin recovery of the aircraft. By providing a CI, which reduced the computational workload even further (by reducing the need for understanding of relative attitude differences), then recovery was instigated more quickly. Both the 10-D and 3-D SART scales appeared to be sensitive to these differences. Also, the construct groupings found by Taylor within the 10-D SART reemerged, showing the same close correspondence to his three generic dimensions. Further, it provides evidence of the diagnosticity of the SART methodology for rule-based tasks within the aviation context.

STUDY 3 - WARNINGS COMPREHENSION

INTRODUCTION

Helmet Mounted Display (HMD) technology offers the facility for the presentation of graphical warnings to the pilot at, or near to, his locus of fixation. These could take the form of visual "icons" or pictures of the warning situation present. The availability of voice technology in the cockpit also allows the generation of speech icons or verbal warning messages for presentation. The aim of both of these types of warning is to inform the pilot as quickly as possible of the nature of the problem facing him, thus allowing him to take correct remedial action immediately. Thus both speed and depth of understanding are important for the pilot to understand and act quickly and correctly.Integrality theory predicted that the use of integral bi-modal information presentation would improve understanding [11]. This study aimed to demonstrate that an improvement in understanding would occur, and that the SART scale would be sensitive to that change.

METHOD

Subjects were presented with either Visual, Auditory, or Both types of warning icon describing real aircraft 'Warning' (high priority/threat) and 'Caution' (low priority/threat) situations. The Visual icons used were generated by Aircrew as being meaningful representations of those situations. The Verbal warning messages were based on the F/A18 Voice Warning System and described the same Warnings/Cautions as the Visual icons. Where both types of icon were presented simultaneously, the situations given in each modality were always matched. Subjects were asked to classify each situation as either 'Warning' or 'Caution' and then to rate the threat associated with it. Response times were taken from the onset of the verbal messages. They were also required to complete a 3-Dimensional SART rating for each stimulus. Twelve non-aircrew subjects were tested, all with normal hearing and vision. Training was given to subjects prior to the experiment to ensure that the situations presented would be meaningful to them.

RESULTS

TABLE 3. MEAN RTs and SART scores for modality presentation conditions.

		VISUAL	AUDITORY	BOTH
RT (sec)		1.64	2.08	1.63
SART	DEMAND	43.62	50.61	45.97
	SUPPLY	55.28	57.37	53.34
	UNDERSTANDING	71.79	73.90	74.76

It can be seen from Table 3 that the shortest response latencies were produced by the Visual icons ($p < 0.01$), with the Both condition being faster than the verbal icons alone ($p < 0.05$). This is contrary to the predictions of integrality theory where the Both condition would be expected to show the shortest latencies. This may be explained by the length of the voice messages introducing a baseline increase on RTs because of the arbitrary point from which timings were taken. This was confirmed during debrief of subjects, some of whom reported waiting until the message was completed before responding even when understanding had been achieved. This is further supported by the results obtained from the 3-D SART scores. It can be seen from these that Understanding was rated as significantly higher for the Both condition thus supporting the integrality hypothesis ($p < 0.05$). The Understanding rating also correlated significantly with RTs within conditions ($r = -0.38$, $p < 0.05$), implying that increased Understanding reduces RTs and that between condition differences in RTs are likely to be the result of experimental artifacts.

DISCUSSION

The results of Study 3 provide further support for the diagnosticity of the SART scale. The experimental task used was entirely 'knowledge based' and thus the scale would be expected to show differences in Understanding scores. It can be seen that variations in information quality produced significant improvements in rated understanding by subjects. These differences are small since only one piece of information was being presented (rather than the multiple sources found in a cockpit, which would be expected to produce greater differences). The amount of weight that can be attributed to them is unfortunately reduced by the presence of a probable artifact in the Response Time measure. However, the significant negative correlation between Understanding scores and RT's implies that the Understanding scale was providing a measure of performance as predicted i.e. as understanding improved then the time needed to perform the task was reduced. Further research will need to be conducted (using more complex multiple information sources) to develop a complete picture, but it seems likely that, where the design variable is understanding/conveyed knowledge, then the SART scale will have utility as a predictor of performance with that system.

GENERAL DISCUSSION

The three studies described here provide support for the SART methodology. Principal Components analysis on the 10-D SART data, for both of the first two studies, revealed very similar construct groupings to those found by Taylor. These seem to correspond to the dimensions of Demand on Attentional resources, Supply of Attentional Resources, and Understanding. This is further confirmed by the inclusion of these generic dimensions as a 3-D SART implementation. The close correspondence between the two sources of data add validity to the existence of the 3-D SART as a meaningful scale. Further, the pattern of the relationships between the SART data and the performance data also support the three dimensional interpretation of the SART scale. Thus, although the definitions of the three generic groupings should not be regarded in any way as absolute, they do provide a useful, low-intrusive alternative to the more time consuming 10-D SART.

These studies also show that SART can have utility for predicting performance on skill, rule, and knowledge-based tasks. For skill-based tasks, it is likely to provide the greatest sensitivity through the Demand group of constructs, whilst for rule and knowledge-based tasks the Understanding constructs are likely to become more important. The utility of the Supply constructs as a diagnostic measure did not become apparent in any of the studies. This may be since the time span of each was short and thus did not highlight differences in supply of attention. Such measures may become more relevant where the period over which supply of attention is required is increased, and maximal supply strategies cannot be maintained. Thus supply constructs may show greater diagnosticity when applied in the more demanding arena of extended real-time flight tasks. Also, effects such as boredom may be sensitive to the Supply domain. Further research is required to identify accurately the role which supply is playing in pilot SA. A better understanding of the relationship between Demand and Supply may also prove useful in the application of workload analysis techniques based on measures of attentional demand [12].

The SART approach has shown itself to have utility in the derivation of a rating technique directly from the knowledge of those operators it was designed to measure. Although the approach was contrasted, earlier in this paper, with other attempts to define SA, it should be noted that the results of each may combine to produce a better understanding of the concept. Considerations of 'Schemata' [1], 'Cognitive Style' [13], and individual differences may prove useful in refining the technique. It can be seen, however, that SART can provide not only a definition of what SA is and what affects it, but also a potentially powerful tool for its measurement. More research is required to develop a method of conjoint scaling for the SART dimensions, to allow the generation of, perhaps, a single numerical value for SA. This would provide a simple but meaningful index of SA between systems. There is also the need for validation of the scale within the more complex and dynamic setting of real-world aviation. It is likely to be within this context that a fuller understanding of the relationships between scale dimensions will be achieved. As the situation facing the pilot becomes increasingly uncertain, then any shortfalls in the scale are likely to become apparent. The ability to maintain self-awareness sufficiently, under the extreme mental and physical pressures facing the pilots of military combat aircraft, to use a subjective rating scale accurately, may prove an important consideration in the application of SART in aircrew systems design.

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ATTENTION GRADIENTS IN SITUATION AWARENESS

by

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SUMMARY

A model of how people develop and maintain situation awareness was explored in a series of four experiments. These experiments focused on the role of attention allocation in situation awareness. All four experiments supported the hypothesis that attention is limited in supply contrary to recently proposed unlimited supply theories. Unlimited supply theories do not predict attention gradients in which more attention is allocated to some things than to others. Spatial awareness data from all four experiments showed that more attention was paid to enemy aircraft that directly threatened the subject than was paid to other aircraft. Experiment 2 showed that the resulting attention gradient steepened as enemy number increased: when attentional demand was increased by increasing the total number of aircraft, subjects seemed to increase the amount of attention paid to direct threats by reallocating attention previously paid to other aircraft. Experiments 3 and 4 provided additional support for the reallocation hypothesis by showing that less attention was paid to individual neutral aircraft when the number of enemy aircraft increased--even though the total number of aircraft had not changed. These data suggest that attention is allocated to objects based on the degree to which they threaten or can assist the subject's task performance.

1. INTRODUCTION

In a rapidly changing tactical situation, how aware are pilots of those factors that should influence their response decisions? When engaged in air-to-air combat, two of the more important questions pilots need answers to include which aircraft are friend, foe, and neutral (FFN), and where each aircraft is at any given moment in time. Answers to these two questions are components of the pilot's situation awareness; I refer to these components as "FFN awareness" and "spatial awareness", respectively. In order to improve these two components of a pilot's situation awareness, new types of information displays may be needed. But what should these new displays be like? If a trial-and-error approach to answering this question is to be avoided, a guiding theory of situation awareness is needed. Such a theory would specify the psychological processes that underlie situation awareness. In two earlier articles, I proposed a theoretical framework that focused on the role of long-term memory in maintaining situation awareness (2, 3). The present paper is more narrowly focused on a series of empirical studies of the role attention may play in situation awareness.

Situation awareness may begin when a limited "supply" of attention is distributed across the elements of a situation (10, 13, 15, 18, 19, 20). Because attention is limited, the person may allocate more attention to some elements than others depending upon the priority he assigns to each. Priorities, in turn, should be determined by the degree to which each element threatens or contributes to successful task completion (compare the role of salience in attention allocation discussed by Wallston, 17). If the elements of the situation are aircraft, the highest priority may be assigned to enemy aircraft that are attacking the pilot. Friendly aircraft capable of assisting the pilot may receive the next highest priority. Other aircraft should receive only whatever attention remains available. This differential allocation of a limited supply of attention is referred to as an attention gradient.

Although intuitively appealing, Hirst (8, 9) and Navon (12, 14) have recently challenged the assumption that the supply of attention is limited. They have argued that attentional capacity is virtually unlimited and that apparent limits in that supply are due to other factors. Hirst suggests that what we think of as "attention" is really some set of skills needed to perform a particular task. Apparent limits in attention arise when those needed skills are not adequately developed. Navon believes that seeming limits to attention appear when "outcome conflicts" arise between components of a complex task (cf., 5). In some ways, these assertions of Hirst and Navon are difficult to refute because they have been able to account for many of the empirical data usually taken to support the limited supply assumption. What may be needed is a demonstration of attention reallocation. Reallocation makes no sense if the attentional supply is unlimited. Therefore, a demonstration of attention reallocation would go a long way towards supporting the limited supply assumption.

The experiments reported here specifically examined whether attention is reallocated from low- to high-priority aircraft when the attentional demand is increased. In experiments 1 and 2, two independent air-to-air combat engagements were shown. In each engagement, one aircraft was under attack from one or more enemy aircraft. Subjects controlled the aircraft under attack in one of the engagements ("relevant" engagement) while the computer controlled the aircraft under attack in the other ("irrelevant" engagement). The two experiments examined the effects of increasing the aggressiveness (experiment 1) and the number (experiment 2) of enemy aircraft on the allocation of attention to the two engagements. In experiments 3 and 4, only one engagement was presented. Two friendly aircraft (one controlled by the subject) cooperatively engaged several enemy aircraft. In addition, several neutral aircraft were in the vicinity of the engagement. These two experiments examined the effects of enemy number as well as "strength" of an aircraft's identity as friend, foe, or neutral on allocation of attention to the three categories of aircraft.

2. EXPERIMENT 1

Experiment 1 focused first on whether spatial awareness would reflect an attention gradient in which more attention would be allocated to the relevant rather than the irrelevant engagement. In addition, the experiment asked whether more attention would be paid to enemy aircraft when they were aggressive, actively seeking out and attacking the friendly aircraft, rather than passive, attacking only when attacked. If more attention is allocated as the degree of threat increases, then spatial awareness should be more accurate when enemy aircraft are aggressive rather than passive. Further, this effect should occur only within the relevant engagement, not the irrelevant one. The reason is that increased aggression in the irrelevant engagement does not threaten the subject and so should not attract more attention. As a result, the attention gradient should be steeper when enemy aircraft are aggressive rather than passive.

In order to measure spatial awareness, the battle was occasionally frozen and subjects were asked to indicate the spatial locations of particular aircraft (see 1, 4, 11). Spatial awareness was defined as the magnitude of subjects' errors in responding to these "location probes".

Method

Subjects

Subjects were 16 paid volunteers from the Wright State University community. All subjects had normal color vision.

Task Overview

In a simulated air battle, subjects controlled one of two friendly aircraft. Each friendly aircraft was independently engaged in combat with three enemy aircraft. The engagement involving the subject's aircraft is referred to as the "relevant" engagement; the other is referred to as the "irrelevant" engagement. All aircraft except the subject's were computer- controlled. In one condition (Aggressive Enemy), enemy aircraft actively sought out and attacked the friendly aircraft. In another condition (Passive Enemy), enemy aircraft attacked only if attacked.

Friendly aircraft were represented by blue circles on the screen. The subject's aircraft was an open circle while the other friendly was a filled circle. Enemy aircraft were represented by squares, triangles, and cross-shaped symbols. Those attacking the subject were red in color; those attacking the other friendly were yellow.

There was a potential confound in the task between engagement (relevant versus irrelevant) and aircraft proximity to the subject's aircraft symbol. The confound would occur if enemy aircraft in the relevant engagement were closer to the subject's aircraft (his or her focus of attention) than were aircraft in the irrelevant engagement. While this confound is difficult to avoid entirely, this experiment was designed to minimize it. Each time an aircraft was destroyed, it reappeared at some random location on the screen. Because of the speed of the simulation, aircraft from both engagements were constantly being destroyed. As a result of this constant destruction coupled with random relocation, individual aircraft from the relevant engagement were often no closer to the subject than were aircraft from the irrelevant one.

Measurement of Situation Awareness

At randomly selected moments, the simulation froze. During this freeze, the subject was tested on the spatial location of one of the aircraft. Which aircraft was selected for this test was random with the constraint that all seven aircraft (excluding the subject's) tested during each trial. The response measure was the subject's error on the spatial location task. At the moment of the freeze, one of the aircraft (referred to as a "probe") disappeared and then reappeared in a box at the bottom of the computer screen. Subjects used a joystick to move the aircraft back to its correct location. Subjects were able to control the aircraft's exact pixel location for this test. Location error was measured as the Euclidian distance (in pixels) between the aircraft and its true location.

Apparatus

The experiment was controlled by a Commodore 128 computer using a Commodore 1702 composite color monitor. Subjects controlled their aircraft with a standard digital, two-dimensional joystick having a fire button mounted on the top. The same joystick was used to respond to the spatial memory probes.

Procedure

Half the subjects were assigned to the aggressive enemy condition; the rest were assigned to the passive enemy condition. Subjects participated in the experiment during three sessions, each about one hour in length. The first session was simply a practice session. Data were collected during sessions two and three only and then averaged across sessions prior to analysis.

Results and Discussion

Data from this and the following experiments were analyzed using the multivariate analysis of variance approach to repeated measures experimental designs (see 16). Normalizing and variance stabilizing transformations were not used (see 6 and 7).

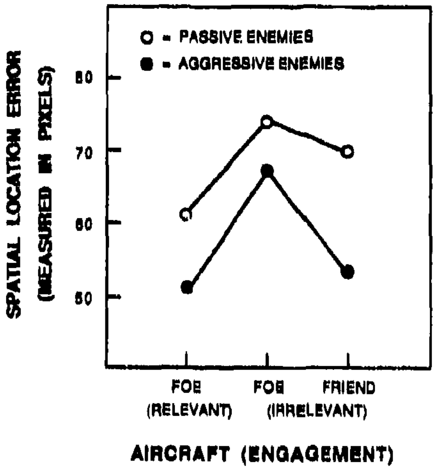

Figure 1. Spatial awareness by engagement and enemy aggressiveness.

As predicted, Figure 1 shows that there was an overall effect of engagement, $F(2,13) = 8.27$, $p < 0.005$. (All reported statistics are from a multivariate analysis of variance (MANOVA) approach to repeated measures data; see 16 for a discussion of this use of MANOVA.) In particular, subjects' spatial awareness was more accurate for enemy aircraft attacking them than for enemy aircraft in the irrelevant engagement, $F(1,14) = 15.44$, $p < 0.002$. This gradient seems to support the hypothesis that attentional priorities are affected by the degree of threat posed by aircraft. Closer examination of the figure reveals an unexpected result. If attention allocation is prioritized based on the degree of threat posed by aircraft, then all aircraft in the irrelevant engagement (three enemies and one friendly) should have received the same amount of attention. The reason is that irrelevant enemy and friendly aircraft are equally non-threatening to the subject. As a result, subjects' spatial awareness should have been unaffected by whether the irrelevant aircraft were friend or foe. But this is not what happened. Instead, spatial awareness for the friendly aircraft was more accurate than for the enemies, $F(1,14) = 8.88$, $p < 0.01$. This result could mean that attention was allocated to the categories of friendly and enemy aircraft before it was allocated to individual aircraft within each category. Since the enemy category was larger, the amount of attention paid to individual enemy aircraft would then be less. Experiment 2 was, in part, an attempt to see if this effect could be replicated.

Figure 1 also shows that the critical interaction between aggressiveness and engagement is missing; that is, the attention gradient was unaffected by whether enemy aircraft were aggressive or passive ($p > 0.28$). Perhaps, knowing that an aircraft poses a direct threat is enough to attract the subject's full attention. Increasing the intensity of the threat seems to have little effect once the threat has been identified. Interestingly, figure 1 indicates that spatial awareness was more accurate when enemy aircraft were aggressive rather than passive, although this effect was not statistically reliable ($p > 0.22$).

The main conclusion from experiment 1 is that the attention gradient predicted by the attention allocation model exists. Although the gradient appears to be a function of threat posed to the subject, the experiment failed to produce evidence for reallocation of a limited supply of attention. Without such evidence, there is no way to be sure that the apparent attention gradient was due to differential allocation of attention rather than some as yet undefined skill or outcome conflict. Experiment 2 was undertaken to address this need.

3. EXPERIMENT 2

Suppose that the number of enemy aircraft in each engagement was increased from one to three. If subjects allocate attention on the basis of threat, then as enemy number increases, spatial awareness should decrease for the irrelevant engagement more than for the relevant one. The reason is that more enemies attacking the subject increases the level of threat to the subject but more enemies attacking the other friendly does not. As a result, subjects should allocate an increased amount of attention to the relevant enemies by "siphoning off" attention previously allocated to the irrelevant engagement. Put another way, the attention gradient should get steeper as enemy number increases.

Method

The method for experiment 2 was the same as that for experiment 1 with the following changes. First, the aggressive- passive enemy manipulation was dropped from the experiment. Second, the number of enemy aircraft in each engagement was varied from trial to trial: there were three enemies in each engagement in one third of the trials, two enemies in another third, and only one enemy in the remaining third. Twenty-two subjects received each enemy number condition three times in a random order.

Results and Discussion

Figure 2 shows the same overall effect of engagement seen in experiment 1, $F(2,19) = 13.78$, $p < 0.0002$. As in the first experiment, subjects' spatial awareness for relevant enemy aircraft was more accurate than for irrelevant enemy aircraft, $F(1,20) = 28.70$, $p < 0.0001$. But unlike in the first experiment, spatial awareness for the irrelevant friendly was not reliably more accurate than for the irrelevant enemies ($p > 0.23$), although the means were in the same direction. Thus, it seems likely that the amount of attention allocated to the irrelevant engagement is simply distributed equally among aircraft regardless of their category as friend or foe.

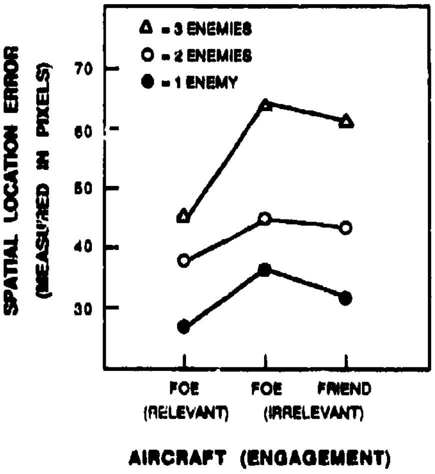

Figure 2. Spatial awareness by engagement and enemy number.

As the number of enemy aircraft increased, figure 2 shows that spatial awareness decreased in accuracy, as expected, $F(2,19) = 53.80$, $p < 0.0001$. In particular, spatial awareness decreased when enemy number increased from one to two, $F(1,19) = 29.99$, $p < 0.0001$; and spatial awareness decreased again when enemy number went from two to three, $F(1,20) = 30.07$, $p < 0.0001$. These results simply confirm the common intuition that less attention can be paid to any one thing as the number of things to be attended increases. By itself, however, this result does not mean that the supply of attention is limited. It may mean only that subjects did not develop some perceptual skill needed to attend to several objects all at once.

Evidence for a limited attentional supply does appear, however, in the critical interaction between engagement and enemy number. The gradient from relevant to irrelevant enemy aircraft appears steeper given three rather than two enemies, although the effect was only marginally reliable, $F(1,20) = 3.10$, $p < 0.10$. In contrast, the gradient given two enemies was the same as that given one ($p > 0.55$). Evidently, when the enemy number increased from one to two, subjects did not reallocate attention from the irrelevant engagement to the relevant one; rather, they paid the same amount of attention to each engagement as before and simply divided that amount across more aircraft. But when the enemy number increased to three, subjects took some of the attention previously paid to the irrelevant engagement and reallocated it to the relevant one.

Although the interaction just described supports the allocation-by-threat hypothesis, the support is not as strong as one might like. Unfortunately, the interaction is weak. Further, the attention gradient did not grow steeper as the enemy number increased from one to two. One explanation for this fact may be that increasing the enemy number from one to two simply did not increase attentional demand enough to trigger a reallocation of attention from the irrelevant to relevant engagement. Logically, a reallocation should occur only if an increase in attention outstrips the amount of attention already allocated. If the overall demand on attention is fairly low so that there is more than enough attention available, then a small increase in demand may not outstrip the amount already allocated--but a large increase might. This line of reasoning suggests that a stronger interaction might have been obtained if the overall demand of the task for attention had been greater.

4. EXPERIMENT 3

The previous two experiments examined allocation of attention to two independent engagements, one relevant to the subject and one not. In experiment 3, only a single engagement was used. In this engagement, two friendly aircraft (one controlled by the subject) engaged either one or three enemy aircraft. In addition, there were several neutral (non-combatant) aircraft within the vicinity of the engagement. According to the allocation-by-threat hypothesis, most attention should be allocated to the enemy aircraft. But attention should also be allocated to the other friendly because it can assist the subject in defending against the enemies. Therefore, the predicted attention gradient is this: most attention is allocated to the enemies, somewhat less to the friendly, and least to neutral aircraft.

Now consider what should happen when the enemy number increases from one to three. Attention previously allocated to neutral aircraft should be reallocated to enemy aircraft up to some limit. Beyond that limit, the amount of attention allocated to any one enemy aircraft should decrease. In order for this reallocation to occur, however, the overall attentional demand of the engagement needs to be high. In order to increase demand for attention, several simulated surface-to-air missile (SAM) sites were distributed throughout the battle area. If subjects allowed their aircraft to stray over one of these sites, their aircraft was immediately destroyed. Further, in order to avoid a confound between enemy number and total number of aircraft, the total number of aircraft was held constant by varying the number of neutrals. When there was one enemy, there were four neutrals; but when there were three enemies, there were only two neutrals.

The manipulation of neutral number means that, as the enemy number increased, half the attention previously allocated to two of the four neutrals could be reallocated to the two additional enemy aircraft; two neutrals are "traded" for two enemies. Of course, this one-for-one reallocation assumes that neutral and enemy aircraft receive equal priorities for attention. If enemy aircraft receive a higher priority than neutrals, then more than half the attention previously allocated to neutrals will be allocated to enemies. This unbalanced reallocation means that spatial awareness for individual neutrals should decrease as enemy number grows; that is, spatial location error for neutrals should grow even though the total number of aircraft had not changed. A potential risk inherent in this prediction is that a ceiling effect may appear in neutral spatial location error. That is, neutral location error may be so large in the first place that it cannot get much larger. In order to compensate for this risk, an additional measure of attention allocation was introduced.

As subjects allocate more attention to a particular aircraft, the association made between that aircraft and its identity as friend, foe, or neutral should grow stronger. Later, if subjects are asked to indicate the FFN identity of a particular aircraft, how quickly they respond should be a function of association strength. Therefore, reaction time to FFN probes should index the amount of attention allocated to individual aircraft, slower reaction times indicating that less attention was allocated. If less attention is allocated to individual neutral aircraft when the enemy number is three rather than one, then neutral probe reaction time should increase with enemy number.

The foregoing logic assumes that aircraft-FFN association strength increases as more attention is paid to the aircraft. Some independent test of this assumption is desirable. One way of testing the assumption is to vary the amount of time that a particular aircraft symbol is assigned a particular FFN identity. The idea is that aircraft-FFN association strength should increase over time. Therefore, a manipulation of FFN assignment duration was introduced into the experiment. On half the trials, the FFN identity of all but the subject's aircraft changed midway through the trial; on the other half, FFN identity remained constant. If association strength increases over time, then the probability of a correct response to FFN probes in general should increase. Thus, the probability of a correct response was expected to be greater when FFN identity remained constant throughout a trial.

Method

Subjects

Subjects were 24 paid volunteers from the Wright State University community. All subjects had normal color vision.

Task Overview

In a simulated air battle, subjects controlled one of two friendly aircraft engaged in combat with either one or three enemy aircraft. If there was only one enemy aircraft, then there were four neutrals; but if there were three enemy aircraft, then there were only two neutrals. As a result, the number of aircraft in the battle was held constant at seven. All aircraft except the subject's were computer-controlled. Each aircraft was represented by its own uniquely shaped symbol. Friendly aircraft were blue in color, enemy aircraft were red, and neutral aircraft were gray. In one condition (Consistent FFN), which aircraft were friend, foe, or neutral was consistent throughout a trial. In another condition (Variable FFN), the identity of each aircraft changed randomly at randomly selected times during each trial.

As in experiments 1 and 2, each time an aircraft was destroyed, it reappeared at some random location on the screen. Because of the speed of the simulation, both friendly and enemy aircraft were constantly being destroyed. As a result of this constant destruction coupled with random relocation, individual friendly and enemy aircraft were often no closer to the subject than were neutral aircraft. Thus, the potential confound between FFN identity and aircraft proximity to the subject's aircraft symbol was minimized.

Measurement of Spatial Awareness and Aircraft-FFN Association Strength

Spatial awareness was measured using location probes in the same way as in experiments 1 and 2, except that all aircraft turned white at the moment of the freeze. This was to prevent subjects from being able to "check" the FFN identities of the aircraft. FFN aircraft-association strength was measured using similar probes that appeared just before or just after the location probe (half the subjects received one order, the other half the other order). The FFN probes worked this way. At the freeze, all of the aircraft turned white, and one of the aircraft disappeared only to reappear at the bottom of the screen. Three letters appeared above the probe (H, F, and I, meaning hostile, friendly, and neutral, respectively). Subjects used a joystick to move a pointer from letter to letter and pressed a "fire button" to make their selection. Subjects' FFN probe reaction time was measured from the onset of the probe display to the first movement of the joystick. In addition, subject's FFN probe responses were recorded as either correct or incorrect. The aircraft tested for spatial location was not the same as the aircraft tested for FFN association. Which aircraft was selected for these tests was random with the constraint that all six aircraft (excluding the subject's) were tested during each trial. The response measures were error on the spatial location task as well as reaction time and percent correct on the FFN identity task.

Apparatus

The same equipment used in the first two experiments was used here.

Procedure

Subjects participated in the experiment during three sessions, each about one hour in length. The first session was simply a practice session. Data were collected during sessions two and three only. During session one, subjects received all four experimental conditions determined by the factorial combination of two variables: whether there were one or three enemy aircraft, and whether FFN identity was consistent or inconsistent. During sessions two and three, subjects received each condition three times. Order effects were counterbalanced using a Latin square.

Results and Discussion

The results provide compelling support for the attention reallocation prediction of the allocation-by-threat hypothesis. Figures 3 and 4 display the effects of enemy aircraft number and FFN identity on spatial error and FFN reaction time, respectively. Interactions are evident in both figures, and both were statistically reliable (spatial error, $F(2,21) = 5.32$, $p = 0.014$; FFN reaction time, $F(2,21) = 7.05$, $p = 0.005$).

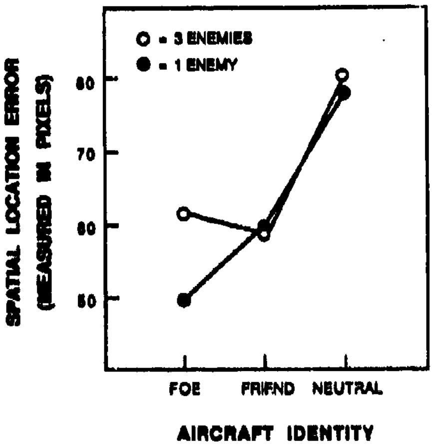

Figure 3. Spatial awareness by FFN type and enemy number.

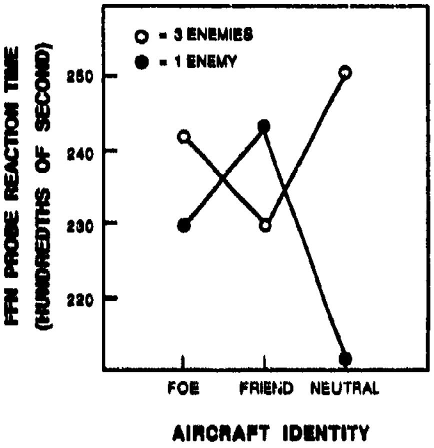

Figure 4. FFN probe reaction time by FFN type and enemy number.

When there were three enemy aircraft rather than one, spatial error for neutral aircraft increased slightly but unreliably ($p > 0.41$), suggesting either no change in attention allocated to individual neutrals or else a ceiling on neutral location error. The FFN reaction time data favor the ceiling effect interpretation: as enemy number increased, reaction times to neutral FFN probes increased dramatically, $F(1,22) = 14.28$, $p = 0.001$. Visual examination of the percent of correct responses to FFN probes revealed no evidence for a speed-accuracy trade-off (see Table 1). Thus, the increase in FFN reaction time seems to indicate a weakening of the aircraft-FFN association for neutral aircraft, and this weakening implies that less attention was paid to individual neutrals as enemy number increased.

Attention reallocation does not seem to be the whole story, however. The FFN probe reaction time and percent correct also seem to reveal a "response preparation" effect that was not (but perhaps should have been) anticipated. When there were four neutrals (one enemy), subjects may have been "prepared" to respond "neutral" to the FFN probe. If so, then responses to neutral probes would have been faster and more accurate than responses to either enemy or friendly probes--just as seen in Figure 4 and Table 1. When there were only two neutrals (three enemies), this response preparation effect should have "flattened out" so that neutral reaction times and percents correct should have been more like those to enemy and friendly probes. As seen in Table 1, this flattening of the response preparation effect is just what happened to the percent correct data. But Figure 4 shows that in the reaction time data, the effect did more than just flatten out; it reversed itself. When there were only two neutrals, reaction times were markedly slower to neutral probes than to either friendly or enemy probes. This reversal is what would be expected if an attention reallocation effect were added to the flattening of the response preparation effect.

FFN reaction times may also suggest that the amount of attention paid to individual friendly and enemy aircraft changed slightly as enemy number increased, but these changes were not statistically reliable ($p > 0.17$; see figure 4). Spatial location error for enemy aircraft did clearly increase, however, $F(1,22) = 10.97$, $p = 0.003$. Evidently, the amount of attention reallocated to enemy from neutral aircraft was not enough to maintain spatial awareness at the same level as before.

Table 1. Percent of Correct Responses to FFN Probes by Aircraft Type and Enemy Number

Enemy Number	Foe	Friend	Neutral
1	61	57	87
3	66	58	61

Figure 3 also displays the spatial awareness gradient predicted by the allocation-by-threat hypothesis. In both enemy number conditions, spatial error for neutral aircraft was greater than spatial error for the computer-controlled friendly, $F(1,22) = 49.97$, $p < 0.0001$. When there was only one enemy aircraft, spatial error was greater for the friendly than for the enemy aircraft, $F(1,22) = 4.54$, $p = 0.034$. There was no reliable difference in spatial error for enemy and friendly aircraft when there were three enemy aircraft, $p > 0.13$. Thus, more attention was always allocated to enemy and friendly aircraft than to neutral aircraft. When there was only one enemy, it received more attention than did the friendly; but when there were three enemies, the difference in spatial awareness between friendly and enemy aircraft disappeared.

Table 2. Percent of Correct Responses to FFN Probes by Enemy Number and FFN Consistency from Experiment 3

Enemy Number	Consistent FFN	Changing FFN
1	84	78
3	72	53

As noted earlier, the foregoing analysis assumes that aircraft-FFN association strength grows with increased attention. The FFN probe percent correct data shown in Table 2 support this assumption. First, percent of correct FFN responses increased as the duration of aircraft-FFN associations increased (that is, when FFN assignments remained consistent throughout a trial rather than when they changed midway through), $F(1,22) = 36.52$, $p < 0.0001$. Second, FFN awareness was better when there was only one rather than three enemy aircraft, $F(1,22) = 140.89$, $p < 0.0001$. Third, increasing enemy number increased the detrimental effect of re-assigning FFN identities, $F(1,22) = 17.84$, $p = 0.0003$. The first result indicates that aircraft-association strength did grow stronger as the duration of the association increased. The second and third results indicate that association strength was weakened as the task's overall demand for attention increased.

5. EXPERIMENT 4

The critical findings in experiment 3 were as follows: as enemy number increased from one to three, spatial location error for neutral probes increased slightly (but unreliably) and reaction time to neutral FFN probes slowed down. Because the reallocation hypothesis is dependent on these results, I decided to make sure they could be replicated. Accordingly, I repeated experiment 3 with eight new subjects and analyzed the resulting data independently.

Means from the eight new subjects are shown in Tables 3 and 4. Table 3 displays spatial error and FFN reaction time means. Table 4 shows the percent of correct responses to FFN probes.

Table 3. Spatial Location Errors (SLE) and FFN Probe Reaction Times (FFN RT) by Aircraft Type, Enemy Number, and FFN Consistency

		Consistent FFN			Changing FFN		
Enemy Number		Foe	Friend	Neutral	Foe	Friend	Neutral
1	SLE	24	69	63	41	52	70
	FFN RT	201	225	203	225	216	186
3	SLE	61	55	71	51	61	83
	FFN RT	240	243	261	231	237	242

Considering first spatial error, the data from experiment 3 were essentially replicated, but this time there was a complicating three-way interaction between enemy number and FFN consistency, $F(2,6) = 22.15$, $p = 0.0017$. When FFN identity was consistent throughout a trial, the spatial error data appeared in about the same form as in experiment 3: enemy number interacted with FFN identity, $F(2,6) = 4.96$, $p = 0.054$. That is, as enemy number increased, spatial location error for neutrals and friendlies was not reliably affected ($p > 0.26$) while the error for enemies increased, $F(1,7) = 6.81$, $p < 0.04$. But when FFN identity changed midway through the trial, an increase in enemy number led to increases in spatial error for both neutrals and enemies; as a result, the main effect of enemy number was reliable ($F(1,7) = 9.81$, $p < 0.02$) while the interaction with FFN identity was not ($p > .71$). Why this three-way interaction appeared in this experiment and not in experiment 3 is unknown. Perhaps it should be regarded as a "fluke". In any event, it appears that the essential feature of the spatial awareness data from experiment 3 are repeatable: as enemy number increases, spatial errors for neutrals increase slightly though unreliably while spatial errors for enemy aircraft increase more dramatically.

As Table 3 shows, reaction times to FFN probes in general slowed down as enemy number increased, $F(1,7) = 5.99$, $p < 0.05$. Reaction times to neutral probes slowed down more than those to enemy and friendly probes, however, producing a marginally reliable interaction between enemy number and FFN identity, $F(2,6) = 3.68$, $p < 0.10$. As in the main experiment, examination of the correctness of probe responses by FFN category showed that the interaction was not due to a speed-accuracy trade-off. Thus, the second critical finding of the third experiment also appears to be repeatable: as enemy number increases, the aircraft-FFN association weakens more for neutral aircraft than for either friendly or enemy aircraft. Note that the response preparation effect evident in the third experiment was replicated as well.

Table 4. Percent of Correct Responses to FFN Probes by Enemy Number and FFN Consistency from Experiment 4

Enemy Number	Consistent FFN	Changing FFN
1	93	86
3	81	59

Finally, the three effects observed in the FFN percent correct data of the main experiment were also replicated, again supporting the logic that aircraft-FFN association strength grows as the amount of attention allocated to individual aircraft increases. First, FFN awareness was better when there was only one rather than three enemy aircraft, $F(1,7) = 53.81$, $p = 0.0002$. Second, FFN awareness suffered when aircraft FFN identity changed midway through a trial, $F(1,7) = 24.19$, $p < 0.002$. Third, the detrimental effect of inconsistent FFN assignments was aggravated by increasing enemy number, $F(1,7) = 12.81$, $p = 0.009$.

6. GENERAL DISCUSSION

The present results support the two main features of the proposed attention allocation model. First, by showing that attention is reallocated as threat intensity increases, the results support the hypothesis of a limited supply of attention. Second, in order to allocate this limited supply of attention across aircraft, subjects prioritize aircraft based on the degree to which those aircraft threaten or assist the subject. In all four experiments, the spatial awareness data showed that more attention was paid to enemy aircraft that directly threatened the subject than was paid to other aircraft. Experiment 2 showed that the resulting attention gradient steepened as enemy number increased: when attentional demand was increased by increasing the total number of aircraft, subjects seemed to increase the amount of attention paid to direct threats by reallocating attention previously paid to other aircraft. Experiments 3 and 4 provided additional support for the reallocation hypothesis by showing that less attention was paid to individual neutral aircraft when the number of enemy aircraft increased--even though the total number of aircraft had not changed.

To the extent that the data demonstrate the reallocation of attention as the threat increases, the results support the hypothesis that attention is limited, not unlimited, in supply (cf., 10, 13, 15, 18, 19, 20). Of course, most people know from daily experience that they seem to "run out" of attention if they attend to too many things at once. But science and common intuition do not always coincide. Hirst's notion of attention as a skill (8, 9) is sufficiently flexible that one might imagine people acting as if they were allocating a limited supply of attention until they developed some necessary skill. One might test this possibility by giving subjects extensive training in the air combat task and seeing if the reallocation effect disappeared over time. But what if the effect did not disappear? Would that prove that attention was not a skill or just that the skill needed more time to develop? It is just this flexibility in the attention-as-a- skill hypothesis that limits its usefulness as a scientific theory--a criticism that has also been leveled at limited capacity theories of attention (8, 9, 12, 14). In any case, the results here are at least consistent with limited capacity theories and seem difficult to explain from other theoretical points of view.

Apart from general support of a limited capacity model of attention, the results specifically support a model in which a limited supply of attention is allocated to task elements according to their ability to contribute to or threaten task success. Spatial awareness in the simulated combat task was best for enemy aircraft that threatened task success, somewhat poorer for friendly aircraft that contributed to task success, and poorest for neutral aircraft that had little impact on task success. Although this differential allocation of attention is not really surprising, it may help to explain some things that are surprising. For example, consider the Iranian airliner inadvertently shot down by the USS Vincennes during the Iran-Iraq War. The attention of Vincennes personnel was allocated to forces that directly threatened their safety. No attention was allocated to the fact that a civilian airliner was in the area. When the airliner was detected on radar, it was confused with a hostile aircraft partly because the information that would have identified it as neutral was ignored. From the viewpoint of the present attention allocation model, this neglect of neutral information was completely predictable. In order to prevent similar occurrences in the future, something is needed to counter the natural tendency to ignore information about neutrals during combat. Unfortunately, what that something may be is not yet clear.

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TOWARDS A FUTURE COCKPIT -- THE PROTOTYPING AND PILOT INTEGRATION OF THE MISSION MANAGEMENT AID (MMA)

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ABSTRACT

The MMA Joint Venture (MMAJV) is a collaborative research project between British Aerospace, Ferranti Defence Systems, GEC Avionics & GEC Sensors, Secretary of State for Defence (RAE) and Smiths Industries Aerospace and Defence Systems. The Joint Venture is a three phase programme, the objectives of which are to

(i) establish the functional requirements and feasibility of a device(s) such as the MMA,

(ii) to prove the techniques for accomplishing this in a rapid prototyping environment and produce a set of functional specifications,

(iii) to optimise the MMA functionality and develop the MMI on a real-time Mission Capable Simulation (MCS).

With the ever-increasing trend towards complex integrated avionics systems and the increased level and capability of threat anticipated in future hostile scenarios, the requirement for the pilot of the single-seat aircraft to maximise his situational awareness at all times must be one of the prime issues in driving the development of such systems.

This paper outlines the requirement for the MMA and introduces the major functional areas of sensor fusion, situation assessment, dynamic planning and the Man-Machine Interface. The paper also discusses some of the Human Factors issues associated with the introduction of an intelligent Mission Management Aid (MMA) and the increasing need to promote situational awareness. Issues relating to the design requirements and evaluation of such systems are also discussed.

1 INTRODUCTION

It is undoubtedly true that the operational requirements for future military aviation, and especially the future single-seat fighter, are becoming progressively more demanding. Traditional roles are being extended and the scenario in which aircraft will be required to operate is likely to be characterised by increasingly hostile and capable threats. In an effort to meet this requirement avionics systems are becoming increasingly sophisticated and integrated and the pilot is required to manage these more capable systems in an increasingly difficult and unpredictable scenario [1].

In contrast to these requirements we seem to hear more and more about the failures of sophisticated and highly integrated systems not so much because the system fails to function, but because it does not produce the performance expected of it. Under these conditions the pilot (or operator) is often cited as a major or contributory factor in the failure and the net result is a loss of confidence in the overall system.

In reality this may be as much a reflection of the design process as an indictment of either human or operational aspects and it is in this sense that the requirement for 'situational awareness' is a fundamental aspect of system design. Unless the designer can identify the requirements of the system controller - the pilot - it is difficult to define the detailed functional specifications for a device such as the MMA.

We may define situational awareness as the pilot's overall appreciation of his current 'world'. This implies both sensory processing and inferencing on the part of the pilot since his appreciation of the 'world' will be determined, in part, by his previous experience and knowledge. An awareness of his own state as well as the state of his aircraft systems, stores, etc, and the current mission situation are all components which contribute to his overall situational awareness. Situation awareness is, in this sense, a Gestalt which is greater than the sum of the parts. An implication of this is that it is difficult to measure as a global metric and is limited in its utility as a tool to predict performance. Indeed, this ties in with reality. It is difficult, even for the pilot himself, to predict situations which will result in a loss or partial loss of situational awareness. A number of factors such as an individual pilot's susceptibility to various stressing tasks/incidents, his physiological state, current level of training, etc, will all affect the way in which he allocates his attention and the amount of resource that a particular situation demands. This, in turn, affects the speed and accuracy with which he perceives the world. Indeed, such is the dynamic nature of situational awareness that it is not clear that the same loss of situational awareness would occur in successive and identical mission situations.

Nevertheless, pilots put increasing importance on their ability to maintain an overall situational awareness and there is an undoubted requirement to understand what factors contribute to this state, to identify their relative importance and thus to ensure that the avionic system enhances the pilot's situational awareness at any instant in time. This, in turn, reflects on the design process. There is a fundamental need to understand what information (as opposed to data!) the pilot needs in a particular mission context, how that information is perceived and how it contributes to his overall situational awareness. This puts the emphasis in the initial design processes, at least, on the user requirements - a pilot orientated approach.

2 MMA APPLICATION

The overall objective of the prototyping phase is to demonstrate the major functions which contribute to the concept of the MMA in an integrated fashion. After consideration of a number of possible missions and scenarios it was decided that to most fully exercise the MMA's functionality the initial prototype should operate in an air-to-ground role although the capability to carry out air-to-air missions will be incorporated in a later phase. In the air-to-ground scenario the MMA will carry out several missions within the current NATO structure and demonstrate its ability to respond to intelligent hostile threats. These are primarily OCA/CAA (offensive counter-air/counter-air attack) and AI (air interdiction) missions.

These missions are strike missions against some strategic/tactical targets such as airfields/aircraft, FOFA (follow-on force attack), command and control centres, etc. They are ideally carried out by a small group of aircraft and are similar in that they are principally stealthy missions demanding minimal use of active sensors, cooperation between aircraft, and a high degree of pre-planning of all mission phases to and from the target. The importance of group operations in future scenarios is unquestionable and an important aspect of the MMA's operation will be to interact with other MMAs to allow intelligent target handoff, attack sequencing and communal planning of resource deployment.

The scenarios are based on a 100 × 200 km gaming area located in the European Central Region and it is intended that the MMA should demonstrate the ability to produce a single view of the outside world through its sensors and a mission plan(s) which is capable of inspection. In addition, the MMA will demonstrate the ability to 'repair' the plan as a function of information updates or unforeseen events.

3 FUTURE SYSTEM REQUIREMENTS AND THE MMA

Sophisticated system design and development often progresses through a logically ordered series of phases each of which builds on, and is more detailed than, its predecessor - a top down approach [2,3]. From initial concept, therefore, the design and development process generally proceeds as in Fig 1.

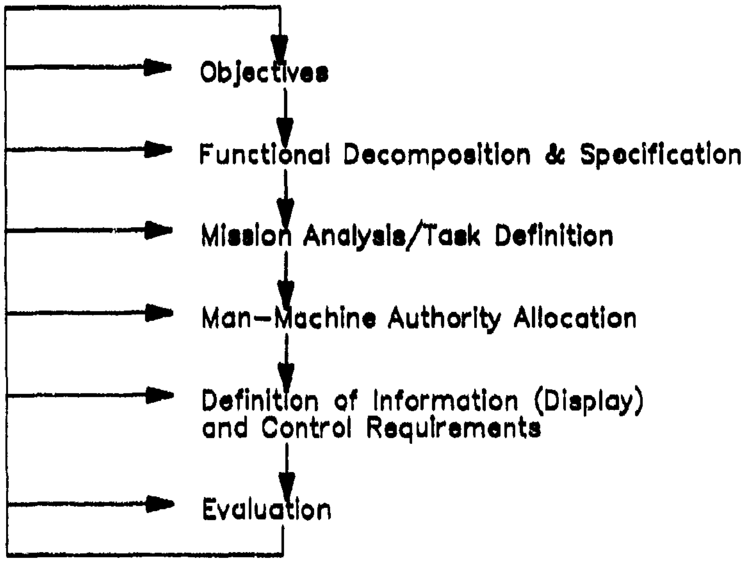

Fig 1 Typical design process

In practice this is typically an iterative process where evaluation may result in a revisiting of any of the stages above it (as illustrated in Fig 1) - even to the extent that it may sometimes modify the objectives!

It is also evident [4] that this is not a completely tenable approach since the implied dependency of each stage on its predecessor may be only partially true. It is difficult, for example, to predict the effect on performance of allocating pilot authority to specific tasks/functions without an understanding of the pilot information and control requirements. This, in turn, may require significant evaluation or research. The inadequacies of a Top Down (or Bottom Up) approach are largely caused by the need for a 'man-in-the-loop' system. Thus a flexible mixture of approaches is required with a significantly greater emphasis on the Human Factors aspects of the system early in the design process. This should result in a product which has a greater prospect of satisfying the customer's needs and also minimises the iterative design/redesign process. This approach is reflected in the MMA design process.

4 MMA CORE FUNCTIONS

Recognition of the need for a more pilot-orientated approach has been embodied in the MMA in that the Man-Machine Interface (MMI) development has been identified as a separate activity which can proceed in parallel with the prototyping of the major functions. Thus the human factors design considerations are seen as important drivers in the design of the MMA itself rather than vice versa. Consideration of the MMI and information display requirements have included examination of fundamental human factors aspects such as the pilot need and benefits of processed sensor information, potential problems associated with knowledge databases of tactics and assessed threat values, the display of optional plans including advice on tactical routeing, the use of resources, etc.

This approach has led to the production of a series of Human Factors guidelines for the MMA [5] and to the derivation of the four major functional areas, as illustrated in Fig 2, viz Sensor Fusion, Situation Assessment, Dynamic Planning, Man-Machine Interface.

These core functions of the MMA provide a tactical plan to the pilot, which he may, wholly or partially, accept or reject. This tactical plan is designed to satisfy the mission objectives. It addresses every aspect of the mission and is visible to the pilot through his cockpit display suite. Alternative (and presumably less favourable) plans are produced and displayed at the pilot's request. There are four main processes involved in producing this tactical plan. Sensor fusion takes data from a number of sources including the on-board tactical database and combines it to produce a single fused view of the out-side world - the Alpha scene. This is combined with intelligence data from the pre-mission brief database to produce an assessed view of the situation - the Beta scene, taking account of the objectives of the current and future mission phases. This assessed view and the overall mission objectives are used to produce a number of tactical options - the plans (or gammas). Finally, the MMI function prioritises the information presented to the pilot and manages the displays and multi-function controls.

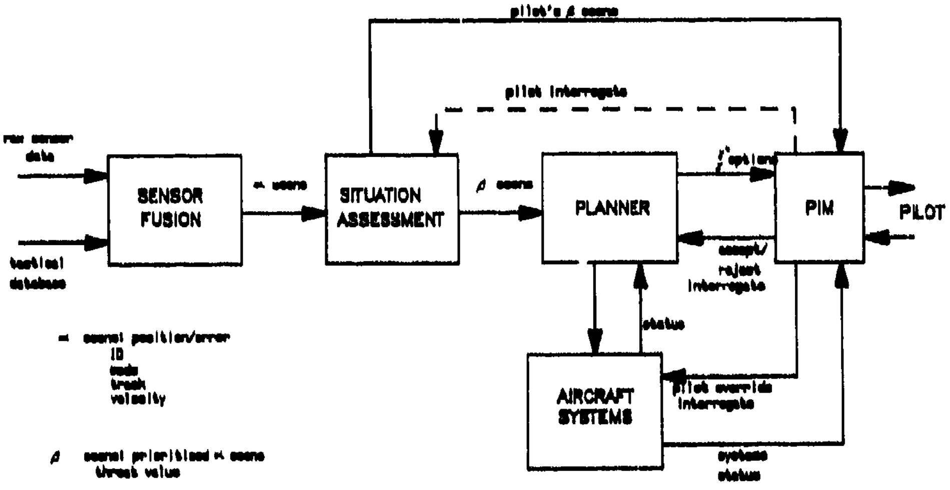

Fig 2 MMA core functions

4.1 Sensor fusion

The sensor fusion function is provided with data from the aircraft sensor systems, communications systems, and the tactical database. This information is processed in two stages to produce an Alpha scene, which is the view of what the aircraft can see in the outside world, together with associated confidence intervals. The two stages in the sensor fusion process are correlation and attribute fusion, and these are described below.

Correlation involves the correlation of tracks into position, and where possible velocities, by the alignment of data from sensors with different accuracies and different temporal and spatial references frames, and the subsequent combining of tracks into a single resolved track with a confidence interval. Secondly, attribute fusion is the identification of targets, using sensor data such as Radar or IR signatures, along with contextual and historical information from the tactical database to separate and identify targets which are possibly spatially indistinguishable.

The output from sensor fusion is the Alpha scene consisting of a list of outside world 'objects' with the positions, velocities, associated confidence intervals, identifications and status where appropriate.

4.2 Situation assessment

The Alpha scene is passed to the Situation Assessment function to produce a Beta scene, which contains a threat-prioritised list of objects. This is a multi-stage process in which firstly the known friendly objects are filtered for separate processing, as although they may not presently constitute a threat, their presence can influence the overall assessment of the threat environment.

Then, the remaining hostile and unknown objects are evaluated for threat and target potential. This evaluation results in inherent threat values being assigned to these objects based on identification of the threat/target and its current relation to the MMA aircraft (*eg* status). These threat values are an integral part of the Beta scene which is displayed to the pilot and are also used in the planner in 'costing' the proposed plan(s).

Thus, the situation assessment process results in a list of objects which, in combination with the recognised friendly objects, constitute the Beta scene. The output Beta scene is of the same format as the Alpha scene, but with the addition of a 'threat' value, priority ordering, and the masking of the uncertainty attached to the original reports.

4.3 Dynamic planning

This is the heart of the MMA which constructs tactical plans (Gammas) including a Gamma* option (the most favourable gamma). The plans are built from the Beta scene input, which provides the planner with the 'current situation', and from the mission objectives provided by the pre-mission brief. The final Gamma* produced contains much more than just a proposed route, for example, the proposed employment of weapon and countermeasure systems, and the three-dimensional tactical route generated by the threat avoidance function, which are fed to the appropriate aircraft systems.

The Planner constructs the tactical plans (gammas) in a data structure whose entries represent parameter values for that stage of the mission and following that particular plan. A search performed through this structure, using techniques appropriate for dealing with a dynamic situation, provides the gamma*. This gamma* is output to the pilot for him to accept or reject before being passed to the aircraft systems. The Planner also has responsibility for monitoring changes in the Beta scene and progress on the plan with a view to 'repairing' the plan when appropriate.

The Planner evaluates options for an Attack/Defence strategy. These options take account of the mission objectives, potential target and threat values and the current status of the aircraft's weapons and countermeasures.

Small scale tactical re-routeing in the air, for threat and terrain avoidance is incorporated at a low level in the gamma(s). The output is in the form of a list of threat-avoiding waypoints for utilisation by the navigation system.

4.4 Man-machine interface

The man-machine interface for the MMA is centred around the Pilot Interface Manager (PIM). The PIM may be considered as a number of functions which 'organise' the information required to be presented to the pilot at any time.

The core functions of the MMA will provide a wealth of information relating to the current situation, proposed MMA actions/solutions, status of systems and cues to the pilot, and the PIM will prioritise this information according to the pilot's current objective. The information required for display is scheduled according to the pilot's current tasking, which will be monitored by the MMA. This scheduling function will continually assess the allocation of task between the pilot and the MMA, and will display the appropriate level of information.

Another important aspect of the MMI will be in ensuring that, apart from the level of information displayed automatically to the pilot, he can easily and naturally access lower levels of information to explain, or qualify MMA advice/plans, etc. This will be particularly important in the evaluation of the MMA, and in pilot training, in order to boost confidence and acceptability of the system.

As described earlier, the pilot will be provided with an assessed view of the outside world, the Beta scene, provided from the situation assessment function. Overlaid on this will be the selected plan or gamma* and the associated status messages and pilot action commands. However, the ability of the pilot to interrogate the system to a lower level (*eg* the Alpha scene), to accept/reject options on the gamma*, to ask 'what if' type questions, and perhaps most notably, to override the MMA are very important human factors considerations for an MMA aircraft.

5 HUMAN FACTORS DESIGN CONSIDERATIONS

The paper has already introduced the notion that there is a need for a shift in the design emphasis of sophisticated and highly integrated systems towards a pilot-orientated approach and outlined the reasons for this shift. The MMI is therefore of fundamental importance to the MMA.

The overall objective of the MMA is to increase the situational awareness of the pilot (and thereby improve overall mission effectiveness) by:

(i) providing him with more complete and higher quality information (*eg* fused sensor data),

(ii) by presenting him with options for dealing with situations using information which he may not have readily to hand (*eg* tactical routeing options),

(iii) by monitoring/informing him of situational changes and system trends as required (*eg* changing threat status, projected out-of-limit system parameters).

The overall objective of the MMI is to present the information which the pilot needs in a fashion which is readily assimilated and to allow him to interact with this information in a way which is appropriate and natural. This implies a certain degree of machine intelligence, for instance, in the areas of displays management, automatic dispensing of expendable countermeasures etc. It also implies a requirement for inferential processes since the MMA should interpret both the pilot's current and future requirements through a knowledge of his goals (*eg* mission requirements at various levels), an evaluation of his needs (*eg* pertinent information to maximise his situational awareness), and interpretation of his actions (*eg* intentional deviations from planned tactical route).

5.1 Situational awareness

This is one particular area in which the MMA presents novel Human Factors problems. The information which is being presented to the pilot at any instant in time is not as predictable as has traditionally been the case and it is essential to ensure that this 'machine-management' of the presented information serves to enhance the Situational Awareness of the pilot rather than to degrade it by presenting information which is unexpected/not required or by changing the character of the displayed information (*eg* revising the tactical route) without priming the pilot or requesting his acceptance.

Another aspect of this problem is that of pilot confidence. Traditional systems are predictable in the sense that there is little in the way of intelligent automation. Under these circumstances it is relatively simple to prove the system and pilot confidence is rapidly established, to whatever degree is appropriate, since system performance expectations are well understood. In contrast, the MMA will have a much larger degree of autonomy. Indeed, there will be occasions when the system puts value judgements on data at its disposal (*eg* dynamic threat assessment). Under these circumstances it is much more difficult to establish pilot confidence in the system since he is no longer sure of machine performance. Further, if he is to accept advice from the system there will be times when he will not understand the reasoning which has led the machine to its current decisions. This is an important aspect of the development and evaluation of such devices and is considered in more detail later in the paper.

5.2 Knowledge elicitation

The process of knowledge elicitation has received much attention in recent years and neither the effort involved nor the necessity for a formal approach should be underestimated. There are a number of levels of machine intelligence but knowledge elicitation is a fundamental Human Factors issue whether we are dealing with 'Artificial Intelligence' or intelligent automation.

Intelligent automation refers to situations, such as displays management, where the knowledge gained by the designer has been used in the design process to determine that specific events will occur under a particular set of operational conditions. The number of parameters involved in satisfying some criterion is usually fairly limited and determined simply when the parameter(s) are enabled or reach some threshold value.

Artificial Intelligence techniques, however, are typically characterised by the use of a number of 'rules' or complex conditionals which are evaluated to determine an appropriate response to particular situations. These rules are either contained as an integral part of the controlling software or set aside in a rule base (as in an expert system).

In the military environment there are at least three levels of knowledge elicitation. At the technical level the respective technologists are an important source of knowledge relating to present and future equipment capability so that the machine can qualify data it receives with knowledge of both its own and possibly enemy equipment. Aircrew are also an excellent source of knowledge relating to operational issues and tactics so that the machine can offer advice based on its understanding of reasonable options, etc. A third aspect of knowledge elicitation in the prototyping of future systems is in the forecasting of the operator's role and how changes may impact system design. The Human Factors specialist has an important role in this respect since he has a good understanding of the human processes and the methods, both objective and subjective, for investigating them. In addition, his view of the operator's role is not restricted by current operational or doctrinal considerations. These three aspects are very complementary and the Human Factors area is the natural focus for this activity reflecting the increasing need for a more pilot-orientated design approach.

5.3 Man-machine authority

The MMA will affect all the major avionic systems of future aircraft (including the pilot!) and the relative level of authority between the pilot and the MMA (or its components) is of fundamental importance in the design of the overall system. Although the MMI will be a crucial issue in determining the success of the MMA a more basic issue, at least in terms of the overall system design, is the man-machine relationship. Thus, it is anticipated that the allocation of function between pilot and machine will be characterised by a certain degree of flexibility to cater for situations where the MMA may relieve the pilot of a particular task (or vice versa). An example of this is the MMA Reflex Response function where the MMA has the authority to deploy countermeasures and, ultimately, manoeuvre in response to a threat to which the pilot either cannot or does not have time to respond. Alternatively, there may be occasions when the pilot requires manual control over a function which is otherwise under control of the MMA, *eg* cockpit moding or deployment of countermeasures. In any event, there will be a need for some reversionary capability at least until such time as sufficient operational experience has been gained to prove the MMA's long term reliability.

The design of inherent flexibility into the allocation of function has obvious implications for the Situational Awareness of the pilot. How does the pilot know the current allocation of function? The design of any such flexibility potentially means that the pilot has to keep a mental track of relative responsibilities, ideally, without any extra cognitive loading. Such a feature may affect his ability to anticipate the actions of the MMA and reduce his Situational Awareness, for example, immediately following an unexpected action or message.

So the issue of Man-Machine authority is a fundamental issue in the design of an MMA and clearly the province of the Human Factors specialist. The Joint Venture is devoting considerable effort to this aspect of the design and the concepts embodied in the prototype design will be evaluated during the Mission Capable Simulation phase of the programme.

5.4 The allocation of function paradox

In endeavouring to define the allocation of function between man and machine it is obviously important to develop an understanding of the capabilities of future systems. However, it is also important to understand the capabilities of the pilot and balance the strengths and weakness of each. Indeed, the level of allocation of function may well affect the way in which information is presented to the pilot (*eg* in its level of abstractness).

5.4.1 Levels of task abstraction

In developing a strategy for the allocation of function, it is necessary to consider which tasks are best suited to the MMA and which to the pilot, how the allocation of authority for these may be influenced by the operational context and the need for duplication of function between the pilot and the MMA. In modelling human performance it is convenient to consider performance based on different levels of activity or response. These levels are often described as activities based on:

(a) Skills
(b) Knowledge
(c) Inference.

(a) Once skills have been developed through extensive training and practice there is a natural limit to the accuracy of that activity which is determined by factors such as human sensor performance, reaction time, manual dexterity as well as environmental factors such as 'g' loading, etc. Fig 3a shows the typical relationship between processing resource and performance and illustrates this natural limit to human performance which is largely unaffected by increasing the amount of resource allocated to it but which can be elevated to a degree by practice. This is particularly characteristic of skill based performance - it is generally overlearned, more or less instinctive and does not require a great deal of high level cognitive processing. Typical examples of these skills might be flight control or weapon aiming. They are, however, susceptible to disruption from competing tasks which may unexpectedly assume a higher priority. Unlike the machine, the human operator is very poor at multiplexing between tasks. Where there is a requirement to multiplex, processing of one task is often delayed until a higher priority one has been completed. In many cases the requirement for the pilot to multiplex often results in a lower quality performance irrespective of response time. This is not normally the case with a machine.

Machines, on the other hand, can normally perform these tasks with an accuracy which is only effectively limited by the resolution of the sensor data, power/speed of the processor, etc. For example, modern aircraft are demonstrably good at flight control or terrain-following tasks. Although it is difficult to demonstrate a machine which learns in the traditional human sense (*eg* through practice) it is likely that, unlike their human counterpart, their performance will continue to improve with future hardware/software developments (Fig 3b). Thus, machines are, arguably, better suited than pilots to tasks characterised by this level of activity especially where there is a frequent need to multiplex between tasks.

(b) The next level of activity is that based on knowledge or previous experience. Responses to threats are typically based on the use of knowledge of systems (*eg* effects of countermeasures). Humans are generally good at this level of activity. Paradoxically, their performance (*eg* response time) often improves with increasing amounts of data.

Machine performance, on the other hand, is usually adversely affected with increasing data. Increasing the knowledge held by the machine invariably increases system response time. In addition, the quality of machine response is directly dependent on the success of the Human Factors specialist in distilling the appropriate information from the 'expert' and synthesising a representative rule set. In an application such as the MMA, where conclusions are not simply correct or incorrect but may be best estimates, this activity is a cornerstone of the entire system.

(c) Inferencing is the ability to reach a decision or to take a course of action based on incomplete data and requires some level of reasoning or projection about possible outcomes or alternative solutions. Humans are particularly good at this activity. It is the ability to make a value judgement (*eg* to put confidence estimates on uncertain data) which is often critical in determining the success or failure of a mission and is the primary reason for the continued existence of the man-in-the-loop. Once again, human performance often increases with increasing amounts of data.

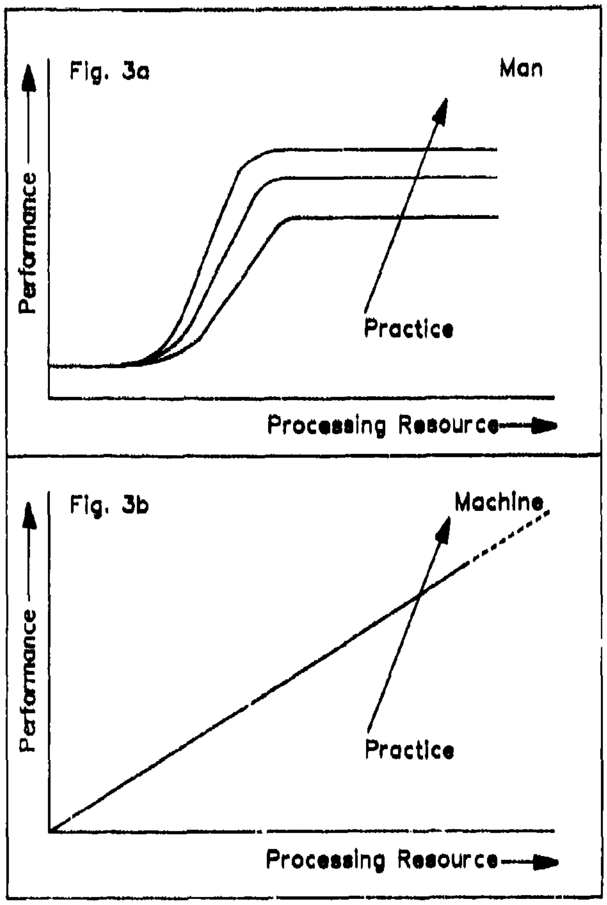

Fig 3 Man and machine resource-performance relationship

It is often difficult to assess machine performance in this area since the criteria for the assessment are often uncertain. This point is developed later in the paper. However, the MMA programme is particularly concerned with prototyping a number of higher level functions which require both knowledge and inferencing. Inferencing is an important quality of the MMA since it may well have access to information which is temporally denied to the pilot or of which the pilot has not taken sufficient account due to high workload and a lack of situational awareness. In addition, machines are completely impartial. They do not exhibit mental 'sets' in the same way as is typical of human processing which affect both the way in which information is perceived and the weighting it is assigned.

It is in this area that the relationship between the man and the machine is most complex and this is reflected in the intention that the MMA should be a pilot aid and not a manager. Thus the MMA provides advice to the pilot, which he must then interpret and place his own value judgement on, unless the situation dictates otherwise.

5.4.2 Flexibility and the allocation of function

Given that the instantaneous workload will, at times, be such that human performance will be degraded, there is considerable potential benefit to be gained from the presence of a machine that can minimise the overall workload level by:

(a) increased use of intelligent automation especially in the systems management area,

(b) the use of Artificial Intelligence techniques to monitor the overall situation and evaluate options or courses of action which, for whatever reason, the pilot may not thoroughly consider such that it can cue the pilot or intervene when appropriate.

If the workload level/task structure were predictable at every instant in time during a mission, and the performance characteristics of the human were known in detail, allocation of function would be a relatively simplistic task. Unfortunately, neither of these are true. The instantaneous level of workload is not generally predictable and therefore there seems to be an inescapable requirement for some level of dynamic allocation of function within a device(s) such as the MMA. This, in turn, requires the MMA to be capable of inferencing and monitoring the overall situation whilst the pilot retains overall control under most circumstances. In order to carry out these functions the MMA has an implicit requirement to continuously evaluate the current situation.

Although the allocation of authority over functions has to retain a degree of flexibility, it is envisaged that tasks which may be adequately characterised by 'intelligent automation' would be most suited to be allocated to the MMA allowing the pilot to allocate more of his resources to decision making based on a heightened situational awareness. These higher level activities would typically take account of advice offered by the MMA, *eg* in respect of alternative tactical routes. Thus, the pilot and the MMA form an interactive, integrated and complementary relationship.

6 MMA EVALUATION

The problems of validating/evaluating AI software are well recognised. Although the software is essentially deterministic its performance may not be predictable in a practical sense in that the rules (or conditionals) which determine the outcome of any particular process are both complex and numerous. Traditional validation techniques are, therefore, often not very productive or sufficient. In addition, avionics systems such as the MMA will be providing advice to the pilot in areas where the pilot may not have sufficient information to adequately assess the accuracy of the answer or where there may not even be a 'correct' answer (*eg* detailed tactical route). Successful integration of an intelligent planning aid such as the MMA requires the acceptance and confidence of the user and it is important, therefore, to develop an understanding of the criteria by which the performance of such a device can be measured.

There are at least two levels at which performance of the MMA may be measured and we may refer to these as the functional level and the operational level. In the MMA Joint Venture these correspond broadly to the prototyping and MCS phases of the programme.

6.1 Functional evaluation

The functional level of evaluation is concerned with assessing the degree to which the MMA software produces a correct and high integrity response to any particular set of conditions. Traditionally this has required testing to demonstrate that the various functions perform to the original specification. In the case of such a sophisticated avionics system, however, it is likely that the original specification will not be sufficiently detailed to allow an adequate assessment in many respects.

In an operational situation it is likely that the MMA will have access to information which is not available to the pilot at any instant in time. It is also likely that the pilot will have knowledge/expertise which is not known by the MMA (*eg* individual experience). Under these conditions the MMA and the pilot form a very complementary pair whose potential joint performance would exceed that of each separately. However, since it is probable that:

(i) the MMA will not usually produce a higher quality plan than the pilot when he has the time, experience and appropriate information,

(ii) the pilot will, on occasions, not be in a position to evaluate an MMA solution, *eg* when the pilot is resource-limited or does not have immediate access to specific information known by the MMA,

it is pertinent to question what is an acceptable MMA decision. It is likely that there is no clear-cut answer to this question since the criteria are likely to be situation specific. For example, it is relatively easy to determine whether the system has moded the cockpit correctly under any given set of conditions. It is much more difficult to determine whether the system has established the optimum three-dimensional tactical route to the target or even whether it has correctly ranked alternative routes.

A possible solution to this is to invoke a system of performance measurement based on criteria which accommodate the degree to which the output can be shown to be satisfactory. To this end a set of criteria are proposed for the acceptance of software such as required by the MMA which necessitates that it:

(1) has the required functionality,

(2) creates 'correct' solutions wherever possible,

(3) provides the pilot with acceptable solutions/options.

Thus, the software should exhibit the required functionality where it is possible to adequately specify this under the range of operational conditions expected (*eg* cockpit moding). Where this is not possible it is required that the software creates 'correct' solutions wherever possible (*eg* production of a true Recognised Surface Picture). There will be circumstances in which neither of these are possible such as when data is qualified with a 'value judgement', *eg* perceived dynamic threat value or perceived cost of resource deployment such as countermeasures. Under these conditions it is suggested that the software should provide the pilot with acceptable solutions/options (as in the proposed use of resources). Using this type of approach it should be possible to optimise the performance of the system and thereby maximise the confidence of the pilot in the capability of his machine.

6.2 Operational evaluation

At the operational level it is important to be able to evaluate the overall system and this necessarily includes the pilot in the evaluation. This provides an opportunity to evaluate the system as a whole and to optimise the efficiency in a variety of areas. The basic objective of this level of evaluation is to establish whether an MMA equipped aircraft is more 'mission effective' than an aircraft without an MMA. A fundamental issue in determining the relative efficiency of the alternative configurations is the relationship between the man and the machine and, at a lower level, the MMI.

To this end the Joint Venture will establish a flexible real-time Mission Capable Simulator (MCS) embodying the MMA. The objectives of this simulation facility are to allow the objective optimisation of the MMA/MMI prototype functions in a realistic environment and to investigate the relative efficiencies of various methods of information presentation and pilot interaction with the system.

In order for the MMA to perform in a realistic manner it will need to base its decisions on a knowledge of enemy capabilities. Thus, in order to plan the most efficient tactical route it should have access to on-board databases concerning information such as surface-to-air missile site response times, tactics and command and control networks. The simulation, in turn, will need to realistically model these aspects of the scenario (and incidentally realistic sensor performance, etc) and a great deal of effort is being allocated to the creation of such an adequate test harness during the early prototyping phase so that the functional evaluation is carried out under similarly realistic conditions.

Although there is a large amount of development work, which necessarily precedes this later programme phase, the man-in-the-loop level of evaluation is progressively becoming a fundamental aspect of system development as the level of system sophistication continues to increase. Indeed, it reflects the increasing importance of the MMI, and the relationship between the man and the machine in future avionics systems, and underlines the necessity for a shift in emphasis towards a pilot-orientated design approach.

7 CONCLUSION

Future missions are likely to be characterised by an increasing number of occasions which will seriously reduce the probability of mission success unless we can ensure that the pilot can react swiftly and effectively. This can only be achieved by ensuring that the pilot can maintain a high level of situational awareness which implies both an understanding of the current situation, the history which has produced the situation and the implications for the future mission situation.

Under high workload conditions there is an obvious need for an MMA which can assist the resource-limited pilot through dynamic management of the workload and provision of appropriate high level information/advice by monitoring, inferring and planning.

The integration of a device such as the MMA poses fundamental questions relating to its operational validation, the man-machine interface and the relationship between the two. Indeed, there seems to be an inescapable requirement for a degree of flexibility in the allocation of function between the pilot and the MMA. Because of the sophistication of this class of avionic device(s) and the continued existence of the pilot-in-the-loop it is argued that neither a top-down nor a bottom-up approach to system design is adequate and the case has been made for a shift in the design emphasis towards a more pilot-orientated approach.

The specification of such a system is difficult and it is less clear what performance is specifically expected from the system. This raises basic questions about the criteria for acceptable MMA decisions/solutions and an approach to this problem based on the degree to which the output has been shown to be satisfactory has been suggested.

These issues are an integral part of the MMA Joint Venture programme. The techniques required by the core functions of the MMA are currently under development in the prototyping phase. It is essential to develop an understanding of the performance of such a class of avionic system in an operational context and an essential step in this direction is evaluation through a piloted Mission Capable Simulation. The Mission Capable Simulation phase will allow real-time optimisation of the MMA/MMI functions in a realistic and intelligent air-to-ground (and subsequently an air-to-air) environment. Using this approach it is anticipated that the MMAJV programme will provide an invaluable contribution towards the development, assessment and pilot integration of sophisticated and integrated systems such as the Mission Management Aid.

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THE THREE-DIMENSIONAL STRUCTURE OF VISUAL ATTENTION AND ITS IMPLICATIONS FOR DISPLAY DESIGN

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Summary

The ability to direct attention toward far visual space while maintaining good spatial orientation is imperative for pilots of high-performance fighter aircraft. In actuality, this task is quite similar to that performed during such everyday activities as reaching and locomotion. A theoretical analysis of the three-dimensional (3-D) structure of visual attention and its involvement in normal perceptual activities leads to the conclusion that far attention is a) biased toward the upper right visual field, b) associated with saccadic scanning confined to the central 30 degrees of the visual field, and c) primarily utilized in performing "local" perceptual processes. In properly designed aircraft displays, then, far attention can be encouraged both by restricting local perceptual analyses to certain regions of the visual field, and by enabling attitude control to be performed using more "global" (ambient) mechanisms.

Introduction

The constant need to transition between the near (cockpit) and far (out-the-window) environments has historically posed one of the most serious challenges--both from an optical and attentional perspective--facing pilots. The major "near" task is to perform the instrument cross-check, primarily to maintain proper aircraft orientation, while important "far" tasks include takeoff and landing, clearing, lead contact, and target acquisition. Until recently, the transition process was made especially difficult because both the pilot's attentional and optical foci were forced inward by the need to maintain spatial orientation via proximal cockpit instruments. Two display concepts have attempted to alleviate the transition problem: the head-up display (HUD) and the wide field-of-view (WFOV) attitude indicator. The first of these is designed to promote a far visual focus by presenting primary flight information (attitude, airspeed, altitude) on a see-through display located at optical infinity. The second approach, typified by the Peripheral Vision Display [1], is designed to facilitate the use of "ambient" resources to maintain attitude control, thereby allowing the pilot's optical and attentional foci to be directed distally.

Unfortunately, neither of the above approaches has been entirely successful in solving the transition problem. First, the HUD does not produce an optical focus directed at infinity [2], nor does it always result in a distal attentional focus [3]. Several reasons have been put forth as to why pilots' accommodation remains in the vicinity of the aircraft during HUD viewing [2,3], including the HUD's bold symbology (which can be seen even if accommodation is slightly displaced inward) and the effects of the HUD frame and windscreen images (which are not at optical infinity and may trap the pilot's accommodation at a reduced optical distance). Also, occlusion and parallax cues clearly create the percept that the HUD is much closer to the pilot than is the outside world. Finally, the failure of current HUD symbologies to allow the pilot to perceive orientation ambiently [4,5] may force his attentional focus to be deployed much closer to the cockpit than to the outside world. This is important since, while attending to a foveated target, we ignore what is perceived to be the background even when it is in the same optical plane [6].

On the other hand, most conventional wide WFOV attitude displays have proven to be unacceptable due to cockpit physical constraints, as illustrated by recent flight tests of the Peripheral Vision Device [7]. Many of the physical restrictions may be alleviated by the use of helmet-mounted displays (HMDs), which can present WFOV attitude symbologies in a relatively small physical area, as well as an optical-infinity symbology free of "frame" effects. But, even HMD technology may not completely solve the transition problem without proper symbology design.

In addition to optical refinements, then, a solution to the transition problem may require a theoretical understanding of how near and far attention are ordinarily deployed during everyday tasks such as reaching and locomotion. The differences between near and far visual perception may perhaps be best understood in the context of the "focal-ambient" distinction [8]. For instance, humans and other primates generally fixate and search for objects located in extrapersonal space using focal-mode processing, while continuing to monitor reaching and locomotory behaviors in or near peripersonal (visuomotor) space in a more ambient mode. Contrary to popular belief, much ambient processing (especially during reaching) is performed within the central visual field at near disparities, so that WFOV attitude displays may not be necessary in order to solve the transition problem. Indeed, it is arguable that a central display has almost as great an effect on our postural control as an equal-area peripheral one [9]. Before discussing how a knowledge of near vs. far visual processing may be applied to instrument design, the nature of near vs. far visual processing (and their associated neural substrates) will be summarized below.

The 3-D Structure of Visual Attention

Based on both theoretical [10] and empirical [11] studies, the structure of visuospatial attention in humans may be most accurately modeled using a cubic structure, with major divisions located along the lateral (left-right), vertical (up-down), and depth (near-far) axes. In a given depth plane, the fundamental (and arguably the most efficiently organized) unit of spatial attention is the quadrant, with attentional facilitation falling off rapidly in both the vertical and lateral directions [12]. The quadrant (or cubic) structure also possesses an ecological validity, as exemplified by the need to monitor arm and hand movements in a specific sector of the visual field (i.e., the lower, contralateral, proximal visual quadrant) during reaching.

The 3-D attentional structure manifests several anisotropies and interdependencies, the most important of which is the bias of the near and far visual systems toward the lower visual field (LVF) and upper visual field (UVF), respectively (Fig. 1). The bias of the near system toward the lower visual field is predicted from the fact that peripersonal (i.e., visuomotor) space is almost exclusively confined to the LVF in primates. The reverse bias of far vision toward the UVF may serve to counteract the LVF bias of the near system, so as to prevent serious attentional and ocular biases from occurring. Indeed, it has recently been shown that divergence and convergence accompany movement of the eyes into the UVF and LVF, respectively [13]. These tendencies may explain why the resting state of accommodation (which is strongly influenced by vergence state) is near the edge of peripersonal space [14], since this accommodative distance would be associated with the resting state of the eyes at a neutral elevation.

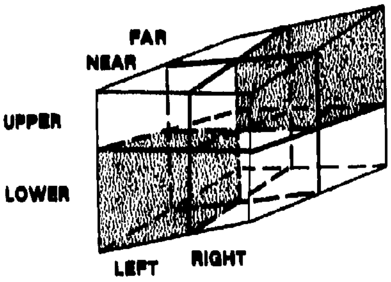


Figure 1. The hypothetical 3-D structure of visual attention, showing various anisotropies and interdependencies. The shaded areas represent the optimal sectors for far vision (upper right) and near vision (lower left) in most humans. The size and shape of individual cubic regions denote attentional emphasis rather than actual physical area. (Reproduced from [4].)

It appears that LVF and UVF processing exhibit many of the perceptual differences expected of regions biased toward near and far visual space. For instance, a recent theoretical review [10] concluded that LVF processing is more global and ambient in nature, corresponding to the fact that we can perform various visuomotor tasks (e.g., reaching and locomotion through visual terrain immediately in front of us) in the LVF without actually devoting a great deal of focal attentional resources to them. A principal reason why global perception is associated with near vision and the LVF is that the images of the arm and hands are frequently optically degraded, due to the rapid motion produced during visuomotor activities and the substantial diplopia and misaccommodation created by fixation on more distant objects (e.g., the object being reached for). In turn, this optical degradation mandates that the perception of form and motion in near vision be carried out via *distributed* processes rather than analyses of *local* contours (see Fig. 2). Conversely, UVF processing is more detailed in nature, consistent with the fact that images in far vision are typically smaller, slower moving, and less retinally disparate. Far visual processing also requires focal visual attention to a greater extent, since many aspects of object recognition (e.g., feature integration) require substantial attentional effort [15].

The principal oculomotor systems used in peripersonal space are pursuit and vergence, with the former almost always being accompanied by head movements. These systems also appear to be biased toward the LVF [10,16]. By contrast, the exploration of extrapersonal space is achieved by means of saccadic eye movements, which are biased toward the UVF [17]. It further appears that the functional visual field during object search in extrapersonal space is limited to the central 30 degrees, which also constitutes the boundary for most naturally occurring saccades [18], especially those which are not accompanied by head movements.

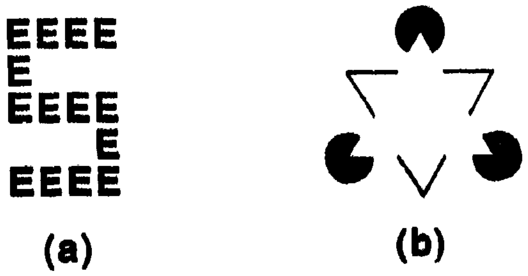
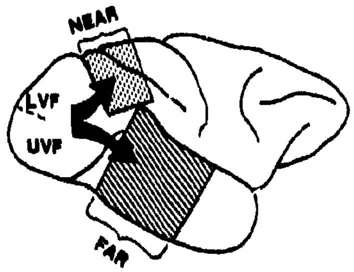


Figure 2. Examples of "local" vs. "global" perception. The small Es in (a) and the disks and lines in (b) require local contour analysis, whereas the large E in (a) and the illusory triangle in (b) require that global correspondences be achieved.

The differences between near and far vision are correlated with differences between the dorsal (occipito-parietal) and ventral (occipito-temporal) pathways of the primate visual system (Fig. 3). The dorsal system is specialized for processing in peripersonal space (e.g., global perception, visually guided reaching, pursuit and vergence movements, etc.), and its neuronal receptive fields are biased toward crossed (near) disparities [10]. The dorsal system is also dominant in vestibular processing, one of the most important sources of information concerning the position of our head and body in space. In turn, this vestibular specialization may account for the parietal lobe's greater role in spatial orientation and visually guided egolocomotion [19,20]. Given the above functional roles, it is not surprising that the attentional system mediated by the dorsal system is biased toward the LVF and peripersonal space, based on an analysis of the "neglect" syndrome [10,21].

Figure 3. The hypothetical representation of near and far visual processing in the primate brain. The dorsal system is a) involved with near vision, b) specialized for global/ambient processing, and c) biased toward the LVF. The ventral system is a) involved with far vision, b) specialized for local/focal processing, and c) slightly biased toward the UVF. The "LVF" and "UVF" markings indicate the representations of these regions in primary visual cortex.



Conversely, the ventral system is specialized for processing in extrapersonal space--e.g., visual search, local perceptual functions, color analysis, and object and facial recognition [10]. Its neuronal receptive fields virtually always include the fovea, are dependent on the animal's center-of-gaze, and possess narrow disparity tuning centered around the plane of fixation. In contrast to the attentional neglect which results from parietal lobe damage, the ventral system is hypothesized to exhibit a reverse attentional bias toward the UVF [10].

In most humans, near and far visual space may be further subdivided into the right and left hemispheres. This may explain why the right hemisphere uses a more global processing strategy than does the left one [22]. There is much evidence suggesting that the left hemisphere is specialized for visual search and object recognition in extrapersonal space [23], while the right hemisphere is more crucial for vestibular processing and the peripersonal attentional system that is biased toward the LVF [10]. (For example, the parietal "neglect" phenomenon is much more frequently encountered following right-hemispheric damage [24]). Since the left and right visual fields project to the right and left hemispheres, respectively, the upper right visual field may, therefore, be the most favored location while attending to far vision, whereas the lower left quadrant may be most closely entwined with near vision (see Fig. 1).

In summary, near and far visual processing appear to be segregated into different neural pathways and hemispheres. Dorsal brain regions (especially on the right side) involved with near vision are specialized for global (ambient) processing, vestibular functioning, and smooth eye movements biased toward the LVF. Conversely, ventral brain regions (especially on the left side) dealing with far vision are more involved in visual search, object recognition, focal attention and other processes biased toward the UVF. The implications of the above distinctions for cockpit display design will be discussed in the next section.

Implications of 3-D Visual Attention for Display Design

As mentioned earlier, the fundamental goal of cockpit display technology should be to allow pilots to direct attention distally while maintaining good spatial orientation. Based on the foregoing analysis, various design features that may facilitate this interaction are described below. These are especially applicable to HUDs and HMDs, whose infinity optics are explicitly designed to promote a distal optical focus.

First, displays should be arranged in a *quadrant* format, as befits the 3-D structure of visual attention. Those types of information which must be frequently checked and whose processing requires focal attentional resources (i.e., altimeter and airspeed readings) should be placed in the upper quadrants, so that the pilot can attend to them without destroying his distal attentional focus. It should be noted that such an arrangement is violated by current moving-tape scales on the F-16 and other aircraft, which extend into both the UVF and LVF. Ideally, the most critical information (altimeter readings) should be placed in the upper right quadrant, where far vision appears to be most strongly biased. This is particularly true when the manual control of altitude (via the stick) is assigned to the right hand, in order to take advantage of additional field-hand compatibility effects [25].

Second, critical information should be limited to a maximum *15-deg radius* surrounding the center of the display, to coincide with the boundary of the feature search field. (In fact, it may be desirable to restrict most focal information processing to still smaller eccentricities, depending on the size and other characteristics of the alphanumeric information in question.) Beyond 15 degrees, humans generally make a combined eye and head movement that is uncharacteristic of our far visual system; indeed, combined head-eye movements are rarely elicited from "far" oculomotor scanning centers such as the superior colliculus in primates [26]. The 30-deg diameter criterion is particularly relevant for HMDs that are physically capable of presenting alphanumeric information at much greater eccentricities. It is also applicable to the dimensions of the overall cockpit instrument panel, which currently exceed this limit. One way to restrict the latter's expanse is via the use of several properly arranged multifunction CRT displays.

Third, the *type of information* presented to pilots should simulate that which is naturally encountered while attending to far visual space. In distal space, we generally see smaller, slower moving, colored forms rather than large, rapidly moving images, and this is the type of information which our far visual system is most adept at processing [10]. Thus, altimeter and airspeed displays should not contain a great deal of movement, even though some "trend" indicators are desirable. The ability to use a combination of alphanumeric information (e.g., in the upper right quadrant) and motion/pictorial cues (e.g., in the lower left quadrant) may further tap into different inter- and intra-hemispheric attentional "pools" and thereby enhance parallel processing over the entire display [27].

Fourth, ambient processing of spatial orientation information may be encouraged either by placing *large* attitude displays at more *peripheral* retinal eccentricities (as is possible for HMDs), or by using *global* perceptual symbologies in *central* vision (as would be required of current HUDs). As discussed earlier, however, a conventional display that is of insufficient total area may not promote effective attitude control, even if presented peripherally. Indeed, it may be far less salient than a centrally presented global display, such as the one shown in Figure 4. This attitude indicator--which is defined by illusory (global) rather than solid (local) contours and is especially vivid when placed in motion--resembles current head-down attitude displays that are generally superior to the HUD pitch-ladder in conveying attitude information [4], in spite of their small size. It also resembles the global forms that are best processed by the dorsal visual system [10]. Despite its see-through character (necessary for HUDs and HMDs), the global attitude indicator is arguably as easily processed as head-down attitude displays that are composed of solid contours. Certainly, the similarity of its shape to that of head-down attitude balls would facilitate positive transfer between HUD and instrument panel crosschecks.

The attitude display in Figure 4 also illustrates another means of rendering the attitude readout more ambient. This approach is to use those preattentive cues which ordinarily aid us in locomoting along the ground (especially in the LVF region just outside the confines of peripersonal space). Such *ecologically valid* cues include relative motion flow, size and orientation, all of which are valuable in extracting the shape, velocity and distance of objects against a textured background [4]. Ideally, a display symbology that depicts the aircraft's orientation relative to the ground should render the latter using real-world cues such as perspective, size and texture gradients, natural horizons, and motion flow. With slight modifications, virtually all of these cues can be included on current HUD pitch-ladder displays without compromising their "see-through" quality [4].

Figure 4. A "global" attitude display, formed by illusory ontours. This display also illustrates good pre-attentive, ecological cueing, including a natural horizon, perspective, and size and texture gradients (motion flow not shown). (Reproduced from [4].)

Finally, a knowledge of how the brain processes certain types of information suggests the type of reference frame that should be incorporated into future attitude displays. As discussed earlier, the dorsal visual system is the site of both near visual proces-sing and visual-vestibular interaction in the brain. While not strictly linked to near vision, the vestibular sense contributes to many visuomotor activities because of its role in signaling the position of the body and head in space. As such, it also serves to stabilize the world, for without vestibular input, visual instability and "field-dependence" set in [28]. Even though vestibular inputs (and dorsal brain areas) are used to infer self-motion in a stable world, the depiction of orientational (attitude) information in conventional displays assumes that the world moves around a stationary aircraft. This fundamental incongruency lies at the heart of the "inside-out" vs. "outside-in" controversy [29]. The inside-out perspective--standard on all USAF aircraft--depicts a stationary aircraft in a moving world (conforming to what is transmitted by the retinal image), whereas the outside-in perspective depicts a moving aircraft relative to a stationary world (conforming to the pilot's perceptual experience).

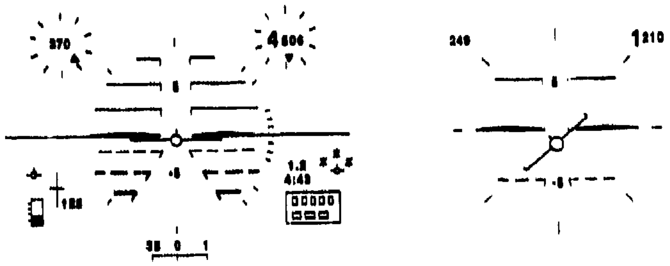
Even though the attitude information on current HUDs supposedly conforms to the image of the outside world as transmitted by the retina, we do not perceptually stabilize it because information in near vision is evidently not stabilized by the vestibular system in the same way that far visual inputs are. In part, this is because of motion parallax (i.e., velocity differences between near and far objects during head and body translations), but it also derives from the observation that vestibular inputs are not used to stabilize small, near objects that are contained in vehicles moving with us. This finding can be easily demonstrated in the oculogravic and oculogyral illusions, in which cockpit images are perceived to move in the same direction as the illusory self-motion [30].

Thus, the "inside-out" perspective may be at fundamental odds with the natural workings of our ambient visual system, consequently directing important focal attentional resources toward the attitude display and away from the out-the-world environment. However, the outside-in perspective should probably be limited to the roll axis, since: a) it is physically difficult to depict 360 degrees of pitch in a small, central display; b) tasks such as weapon delivery and landing may demand more "conformality" with the actual retinal image in the pitch axis, as aircraft roll does not affect the relative linear positioning of target and aircraft; and c) the outside-in perspective has empirically been shown to be more effective for roll than for pitch [31].

Conclusions

In summary, a solution to the transition problem facing pilots may lie in an understanding of the way near and far perceptual and neural processes are normally carried out in humans. The most important elements in this interaction are the biases of near and far visual attention toward the UVF and LVF, respectively, and the different types of processing performed in these two different realms--global/ambient (near) vs. local/focal (far). Based on a theoretical model of 3-D attention, the following represent important guidelines for directing the pilot's attention toward far visual space. First, primary flight displays should, in addition to being collimated, adopt a quadrant format, with important alphanumeric information (airspeed and altimeter data) presented above the fixation point. Second, all alphanumeric and other information requiring "focal" visual processing should be confined to the central 30 degrees in order to avoid those head movements which momentarily disrupt the pilot's attentional focus, and should not be presented using substantial motion. Third, attitude displays should tap into more global or ambient processing by a) requiring Peripheral visual resources to be used whenever possible, b) using a global format when the display is restricted to central vision, c) embracing an ecologically valid, preattentive cueing format, and d) selecting a split frame-of-reference (e.g., outside-in for roll), which most conforms to the way in which we perceptually stabilize the far visual world.

Prototype displays (originally designed for HUDs) which adhere to these guidelines are shown in Figure 5. The quadrant arrangement, ecological cueing, global attitude format, and outside-in frame-of-reference for roll are all apparent in these displays. In many important respects, however, these displays do not radically depart from previous concepts or even current symbologies. Preliminary evidence indicates that the outside-in version of these displays compares favorably to other current and prototype displays in terms of unusual roll-attitude recovery [32], and that thickened negative pitch lines (simulating size gradients) are particularly effective in improving discrimination of positive vs. negative pitch attitudes [33].



(a) (b)

Figure 5. Prototype HUD displays which follow the guidelines listed in text. A full-format display is shown in (a), while a decluttered one is shown in (b). (Reproduced from [4].)

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A REAL TIME EVALUATION OF THE USE OF A PERSPECTIVE FORMAT TO PROMOTE SITUATIONAL AWARENESS IN USERS OF AIR TO AIR TACTICAL DISPLAYS

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ABSTRACT

Networked data systems such as JTIDS (Joint Tactical Information Distribution System) promise a substantial increase in the amount of information available to aircrew involved in air defence. This will include more detailed information regarding relative heights of hostile and friendly airborne units. Such information will be an important factor in BVR (Beyond Visual Range) air defence engagements using missiles such as AMRAAM (Advanced Medium Range Air to Air Missile). On the basis of psychological theory it was predicted that a perspective display format, would allow a greater volume of situational awareness data to be shown intuitively than would be the case with a conventional plan format. Specifically it should allow information regarding relative height to be more easily comprehended.

A real time, cockpit based, air defence simulation was used to compare pilot performance using a perspective situational awareness display with performance with an equivalent plan view display. 12 subjects were instructed to attack and destroy a constantly evading target aircraft that had to be distinguished from a number of hostile aircraft. Performance measures showed that subjects had more difficulty in learning to use the perspective display. However once they were familiar with this format their results were significantly better than those achieved using the plan display. These results are discussed with reference to requirements for air defence displays in general and networked data displays

COUNTERAIR SITUATION AWARENESS DISPLAY FOR ARMY AVIATION

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SUMMARY

An air combat display concept is proposed for Army aviation helicopter cockpits. The effects of the choice of the display size, the display symbol size, and the area of coverage as a counterair situation awareness display are discussed. The display shows the tracks of aircraft about the host helicopter on a Planar Position Indicator (PPI) graph via the open broadcast radio net of the division-wide air defense radar coverage. The display is used to alert the aircrew to the presence of aircraft in the area and cue to the location of enemy threats for the counterair role.

It is concluded that with the relatively small display sizes used in helicopters, an accurate determination of the position of enemy threats during air-to-air combat cannot be made by an aviator from the PPI alone. It must be interactive allowing access to detailed information about a track of interest to be useful.

INTRODUCTION

In early 1986, the Army indicated a need for a combined arms counterair approach to accomplish the traditional air defense mission. In the summer of 1986, the U.S. Army Training and Doctrine Command (TRADOC) renamed the mission area that forms the basis for developing air defense doctrine, training, force structure, and material to the 'Counterair Mission Area.' Since that time, the name has been changed to the 'Air Defense Combined Arms Initiative.' Included in the Combined Arms Initiative are seven primary functional areas: infantry, armor, aviation, air defense artillery, field artillery, intelligence and electronic warfare, and command, control, and communications. Air defense artillery (ADA) is the key player. After ADA, the most significant contribution will come from Army aviation.

This means that Army helicopters will engage in air-to-air combat operations to help defeat the air threat. As a result, the Army intends to mount Stinger missiles on some of its helicopters currently in the inventory.

It is envisioned that the Forward Area Air Defense Command, Control, and Intelligence (FAAD C^3I) system, now being developed, will provide the net required to link together ADA, aviation, and other elements of the Combined Arms Initiative. The key information to be transmitted is the relative location of friendly and enemy aircraft in the battle area.

Those helicopters equipped with Stinger missiles will require a cockpit display capable of presenting FAAD sensor data to the aircraft. The information displayed is the 'air battle picture' as provided by the FAAD sensors via the FAAD C^3I system. The primary purpose of this display is to alert and cue the aircrew to the presence and relative location of air threats on the battlefield. The display can also be used to designate threats as targets and to hand over targets for engagement.

Heading, airspeed, and altitude data are available for each aircraft on the battlefield detected by the FAAD sensors. In addition, bearing and range from our own aircraft to the threat aircraft and the time to first launch can be computed by on-board processors.

PURPOSE

This report describes the air combat display analysis completed by the Aviation Team of the Aviation and Air Defense Division at the U.S. Army Human Engineering Laboratory (HEL) at Aberdeen Proving Ground, Maryland. It addresses the issues of providing an air combat display for Army helicopters. The work was in support of an October 1987 request by the U.S. Army Aviation Center (USAAVNC) of HEL to examine the issues of displaying the FAAD sensor data in the cockpit of Stinger-equipped helicopters.

BACKGROUND

In this section of the report, we describe the FAAD C^3I system, the air-to-air environment, helicopters, missions, and the tactics, as well as the role of aviation command and control, and the situational awareness requirements.

The FAAD C^{3}I System

The automated FAAD C^{3}I system, presently being developed, will consolidate aircraft track information from an array of sensors within the division area: short range FAAD sensors along the forward division area, long range, high altitude Patriot acquisition radar sensors in the rear Corp area, and the Air Force's airborne warning and control system (AWACS). The coverage will extend over the division's forward and rear areas, and beyond the division's forward-line-of-troops (FLOT).

The information will be correlated and each track classified as friendly, enemy, or unknown according to: electronic identification, friend or foe (IFF), aircraft performance, known friendly flight missions, and flight patterns and actions. In this manner, the FAAD system will distinguish friendly from hostile aircraft. When positive identification of friendly or hostile aircraft cannot be made, the aircraft is categorized as unknown. The FAAD sensors can also differentiate between fixed-wing and rotary-wing aircraft.

The resulting aircraft information (track location, identification, wing type, number, speed, and altitude) is to be broadcasted periodically, along with air battle status conditions and alerts, battlefield geometry on an open net to the ADA fire units, the aviation elements including the aviation tactical operation centers, and air-to-air combat flight elements.

Situation awareness will be provided to the pilots of all Stinger missile-equipped helicopters via the Enhanced Position Location and Reporting System (EPLRS). This system has been selected by the air defense community to provide the communication link for the FAAD C^{3}I network (Casper and Szczerba, 1988).

Air-To-Air Flight Missions

The air-to-air flight missions have not been fully defined, but several types are being considered. One mission would be as mobile air defense elements helping to defend division assets against enemy helicopter strikes behind the FLOT. In this case, an air-to-air flight element would be vectored by the battalion's air battle management officer to intercept the strike possibly in conjunction with ground ADA elements.

Another task for an air-to-air team would be as escort for any of the standard helicopter missions: aerial observation to observe and direct fire support as well as gather and report intelligence information, anti-armor strikes, air assault troop insertions and evacuations, and any air movement operations to relocate personnel, supplies, and equipment. The development of air-to-air attack helicopters by the Warsaw Pact nations necessitates the development of escort tactics for defense of these missions.

Air-To-Air Combat Helicopters

The Army is considering two helicopters in the current inventory for the near term air-to-air role: the OH-58D, and the AH-64 Apache. The aircrafts would be fitted with Stinger heat-seeking missiles (Philips, 1988). A prototype version of the AH-64A gun system, coupled to a helmet-mounted display, is being developed for close-in air-to-air combat (Buresh, Parlier, and Wilson, 1988).

The Army is developing the lightweight, multifunctional, high performance, experimental (LHX), scout/attack assault (SCAT) helicopter series. One version is expected to be an advanced counterair fighter equipped with an early warning system, a situation awareness digital map display, and air-to-air fire-and-forget missiles.

Other helicopter models being modified or developed for the escort role by NATO forces are the French Army's Gazelles and their successor, the Helicoptere d'Appui-Protection (HAP) version of the Franco-German combat helicopter, and the German Army's planned BSH-1 (version BO105) for escort and anti-helicopter duties (de Briganti, 1988).

The Soviet Mil MI-24 Hind-E assault helicopter, employed by the Warsaw Pact nations, is reported to have an air-to-air capability (Harvey, 1988). The Mil MI-28 Havoc and the projected high-speed Kamov Hokum under development by the Soviets are reported to be air combat helicopters, designed especially to shoot down the U.S. AH-64 Apache attack helicopters because of their estimated 15 tanks to one helicopter kill ratio (Barber, 1987).

Air-To-Air Combat Environment

The essential features of combat between helicopters can be abstracted from known experiments and simulations. The U.S. Marine Corps' Aviation and Tactics Squadron No. 1 and the Utah Army National Guard Attack Helicopter Troop of the 183rd Armored Cavalry Regiment, participate twice a year in air-to-air combat training exercises using Bell AH-1 Cobra gunships equipped with AIM-9 Sidewinder heat-seeking missiles (Barber, 1987; Toler, 1987). In Europe, the French Army's Light Air Arm (ALAT) has been studying air-to-air combat for several years using their Gazelles squadrons equipped with 20-mm cannon and Mistral missiles (Gannet, 1988).

One lesson learned from these exercises is that air-to-air combat will be dominated by the terrain which influences the flight patterns, the intervisibility, and the infrared signature. The combating helicopters will be forced to fly nap-of-the-earth (NOE) to reduce detection and hostile fire. The NATO forces fly slowly and close to the ground, making maximum use of terrain and vegetation cover so as not to be seen. In contrast, the Warsaw Pact forces tend to fly fast while hugging the terrain contours, using their speed to attain surprise. The actual speed at which the aircraft maneuvers will depend on the terrain. A slow speed would be maintained over hilly country with dense forest; maximum speed would be attained over flat, featureless desert. Caution would be necessary in mountainous country (Cannet, 1988).

The maximum range at which enemy helicopters can be visually detected depends upon the terrain, lighting conditions, helicopter size, and the optics used. The detection range is farther for an aviator who has been alerted and cued to the location of the opposing aircraft, than the range for an aviator merely searching for opponents. The addition of a situational awareness display to the cockpit alerts the aviator and cues him [illegible] the direction to search for the target. It is by facing the probable direction [illegible] approach of the enemy that an aviator can hope to see the enemy before being seen (Cannet [illegible] 988).

The aviator who detects his adversary first, controls the engagement. As stated by Cannet (1988), 'He has the choice of bringing his weapon to bear and firing as soon as he is within range; or of closing the range still further and opening fire only when the enemy, finally detecting him, begins to train his own weapon; or of masking himself behind terrain and then choosing whether to avoid combat, wait in ambush or maneuver into the enemy's rear.'

Once the aviator has identified the opposing helicopter as hostile, he must manuever his aircraft to bring the enemy into the lethal zone of his weapon system. The choice by the U.S. Army of Stinger heat-seeking missiles as offensive weapons limits the lethal zone. The heat-seeking missile has a pre-launch delay which may prevent firing when fighting low flying helicopters in broken terrain. Furthermore, there is a minimum range below which the missile will not manuever. The missile requires high infrared radiation from the target in order to allow lock-on at long range (Cannet, 1988). For these reasons, the pilot must select his approach, especially in broken terrain, and have the enemy in sight at a range to sufficiently activate and fire the missile.

The evidence suggests that a 'dogfight' scenario involving aerobatic flight between two opposing helicopters is impractical. Helicopters will face several threats simultaneously, including air defense artillery and fixed-wing aircraft as well as other helicopters. Masking maneuvers will be more practical than aerobatics over the European terrain (de Briganti, 1988).

Command and Control

The proper utilization of command, control, and intelligence is necessary for winning the air battle. The maneuver commander must establish engagement measures against threat helicopters and determine target priorities within his sector. The air defense officer will be receiving threat aerial target information from the FAAD C^{2}I network. It should be the responsibility of the air defense officer at a center location and level of command, possibly the maneuver brigade commander's tactical operations center (TOC), to categorize and prioritize the intelligence information received from the FAAD C^{2}I network so that the maneuver commander can make the right decision.

In the case of aerial threat, the maneuver commander could redirect an operationally controlled attack helicopter unit from killing tanks to engaging the enemy helicopters. Once the order is received to pursue an air combat role, the attack helicopter unit commander could direct all aircraft to monitor the air defense net, thus allowing everyone in the flight to maintain situational awareness and the capability to receive cueing. The aviation commander would maintain his command and control on the unit's internal communications network (Casper and Szczerba, 1988).

Situational Awareness Display Requirements

The combat aviator depends on the situational awareness display to provide information of value on the tactical state-of-the-threat environment and his spatial orientation and position in that environment. The display must provide information in a format that is useful to the aviator at each stage of target engagement: alerting, cueing, target selection, selection of fire positions, target acquisition, identification, and engage fire. The alerting and cueing are performed on the display, perhaps in conjunction with the aviation command and control net. Target selection is made from the display or dictated by command.

The selection of firing positions during the combat mission involves many factors. The aviator must consider the threat (weapons, radars, number of threats), intervisibilities to the threat, availability of terrain masking, weather, distance, fuel available, and ingress/egress routes. The target acquisition is a visual process which orients the aviator to the target from the display. Identification and engage fire follow visual acquisition.

DISPLAY ANALYSIS

In this portion of the report, we describe a multifunctional cathode-ray tube (CRT) combat display concept for Army air-to-air combat helicopters. We consider two display formats: (1) a far distance display for alerting and cueing, and (2) a near distance format for target selection and acquisition.

Display Information Requirements

General

As mentioned previously, the information displayed is the 'air battle picture' as provided by the FAAD sensors via the FAAD C³I system. The primary purpose of this display is to alert and cue the aircrew of the presence and relative location of air threats on the battlefield. In addition, the display can be used to designate threats as targets and to hand over targets for engagement.

Heading, airspeed, and altitude information is available for each aircraft on the battlefield detected by the FAAD sensors. In addition, bearing and range from our own aircraft to the threat aircraft and the time to first launch can be computed.

Symbology

One of the earliest questions became the selection of symbology to represent the various aircraft on the battlefield. The FAAD sensors can differentiate between fixed-wing and rotary-wing aircraft. To a degree, the sensors can also distinguish friendly from hostile aircraft. When positive identification of friendly or hostile aircraft cannot be made, the aircraft is categorized as unknown. Therefore, symbols representing friendly, hostile, and unknown aircraft as well as fixed- and rotary-wing aircraft are required. Symbology for this purpose is already in use by the air defense community and is published in DoD-STD-1477 (Department of Defense, 1983). The decision was made to use the symbology in DoD-STD-1477 as a baseline to determine its suitability for a cockpit display. The symbology will be discussed in the Air Combat Display Concept section of this report.

Area Of Coverage

The question about the area of coverage asks, if we have a cockpit display in which the 'own aircraft' symbol is located in the center, what radius or range from the center should be displayed? The answer is related to the requirements for timely alerting and cueing. To determine the area of coverage suitable for helicopter applications, an analysis of a selected mission scenario was conducted. The results of this analysis are presented in the Approach section of this report.

Display Hardware Characteristics

Display size and resolution determine the effectiveness of providing meaningful alerting and cueing information. Because of the limited cockpit panel space available in a helicopter, four display sizes are considered in that section: (1) a 3-by-3-inch display, (2) a 5-by-5-inch display, (3) a 7-by-7-inch display, and (4) a 9-by-9-inch display. The resolutions considered for these display sizes are 38 raster lines per inch, appropriate for 7-by-9-font alphanumeric characters, and 96 raster lines per inch, appropriate for detailed map graphics. These issues are discussed in greater detail in the Approach section.

Soldier-Machine Interface

For either of the displays just mentioned, provisions and procedures must be developed that allow the crewmembers to interact with the air combat functions of the display. The displays are used for multiple functions, and it is important that the time and attention required of the crew to interact with the display be kept to a minimum. The soldier-machine interface was given only cursory attention during this effort because the primary emphasis was on developing the display content.

ANALYTICAL APPROACH

This section describes the approach taken to address the issues of area of coverage and symbol size and its effect on the display as an alerting and cueing aid.

Display Area of Coverage

To properly alert and cue the air-to-air aviator to the location of the enemy helicopters, a proper area of coverage is needed. The display should cue the aviator far enough in advance so that he has enough time to select his firing position and maneuver to that position before the enemy reaches it. This analysis is based on a worst case scenario in which friendly anti-armor helicopters are assumed to be engaging a column of enemy tanks.

A flight of enemy helicopters is dispatched to provide support to the armored column. For this analysis, it is assumed that the enemy helicopters are contour flying at a speed of 180 knots. It is also assumed that a friendly air-to-air helicopter team, armed with air-to-air missiles, is providing cover for the helicopters attacking the tanks and that the air-to-air helicopters will maneuver nap-of-the-earth at a speed of 30 knots to an ambush site 5 km away from the tank column to intercept the approaching enemy helicopters at a 5-km stand-off range. At 30 knots, it will take 5.4 minutes to reach the ambush site. In 5.4 minutes, the enemy helicopters travel 30 km. When the 5-km distance to the ambush site and the 5-km stand-off range are added to the 30 km, it results in the friendly helicopters requiring a 40-km alerting in order to respond, maneuver to the ambush site, and engage the enemy helicopters. Based on this worst case analysis, an air combat display with our own aircraft symbol located in the center should provide at least a 40-km radius (80-by-80-km area of coverage). For this particular mission scenario, any smaller range would not provide alerting soon enough for the friendly helicopter force to react and ambush the hostile helicopter force.

This mission scenario requires that sufficient time be allotted for the friendly cover force to maneuver to an ambush site 5 km away to keep the threat helicopters out of engagement range of the friendly anti-armor helicopters. Compared to other air combat operations in which attack positions are predetermined (Department of the Army, 1988), it appears that this type of mission requires maximum alerting times and distances.

Eighty-by-eighty kilometers is a large area to present on the small display surfaces available in Army helicopters. Obviously, if the speed of the enemy helicopters is slower or the speed of the friendly helicopters is faster, the distance traveled by the enemy helicopters decreases and the display area of coverage can be decreased. The airspeeds for the helicopter were selected based on known threat and friendly tactics and doctrine. The selected threat airspeed is at the high end of the range and the selected friendly airspeed is at the lower end providing a worst case scenario. Table 1 shows the effect of increasing or decreasing the speed of the friendly helicopter force.

Table 1

Display Area of Coverage

Friendly Helicopter Force		Hostile Helicopter Force	
Airspeed (Knots)	Flight Time (Minutes)	Flight Distance (Kilometers)	Display Area (Kilometers)
25	6.1	45.0	110 x 110
30	5.4	30.0	80 x 80
40	4.1	22.5	65 x 65

In the remainder of this report, we assume that an appropriate size for the target acquisition display is a 30-km square. The selection displays a 15-km radius area about the host helicopter. The air-to-air combat aviator can see the tracks within the nominal 5-km engagement range of his missiles. He also sees the aircraft approaching his immediate area in time to take defensive action. This is the choice selected by the USAAVNC, and reflects the opinion of most helicopter pilots we interviewed. As determined from the analysis above, however, the area may be too small for the aviator to have sufficient time to select his firing position and to manuever to that position during the alerting and cueing phase of combat.

Display Symbol Size

Using MIL-HDBK-759 (Department of Defense, 1975) as a guide, the display symbol used to represent an aircraft track should subtend at least a 20-minute viewing arc at the crewmember's eye in order to read the symbol and modifiers. Our experience has been that a 25-minute sized symbol would be preferred by aviators in the high task loadings and vibrations of helicopter flight. The nominal viewing distance from the eye of the pilot to the air combat display on the panel of most modern helicopters is 28 inches. The symbol size should therefore be 3/16-inch by 3/16-inch squared.

Symbol Obscuration

Table 2 shows the amount of display area that the symbol overlays or obscures for the two areas of coverage and the four display sizes. The table shows the 30-by-30-km and the 80-by-80-km areas of coverage. The display sizes are 3 by 3 inches, 5 by 5 inches, 7 by 7 inches, and 9 by 9 inches. The table shows that the symbol can overlay from a 0.62-km square of display area to a 5.3-km square depending on the area of coverage and display size. This would be the amount of area hidden from view on a digital map display, as well as the uncertainty in the corresponding track's position.

Table 2

Symbol Obscuration in Kilometers

Display Area of Coverage (Kilometers)	Display Size (Inches) 3 x 3	5 x 5	7 x 7	9 x 9
30 x 30	1.88 km	1.12 km	0.80 km	0.62 km
80 x 80	5.00 km	3.0 km	2.14 km	1.67 km

Display Area of Coverage Resolution

Table 3 lists the display area of coverage resolution in meters; this is the distance on the area of coverage between adjacent pixel points on the display. This is a measure of the accuracy with which items may be located on a digital map display. The table shows that the display area resolution can vary from 762 meters to 37 meters depending on the display size and resolution.

Table 3

Display Area Resolution in Meters

Display Area of Coverage (Kilometers)	Display Resolution (Lines/in)	Display Size (Inches) 3 x 3	5 x 5	7 x 7	9 x 9
30 x 30	35	285 m	171 m	122 m	95 m
	90	111 m	66 m	47 m	37 m
80 x 80	35	762 m	457 m	326 m	254 m
	90	296 m	177 m	127 m	99 m

Given the 3/16-by-3/16-inch symbol size, Table 3 shows the effect of the area of coverage and the display size and resolution on symbol movement. For example, an aircraft being tracked on a 5-by-5-inch display with 90 lines per inch resolution and a 80-by-80-km area of coverage, must travel a distance of 177 meters for the corresponding symbol to move one pixel on the display.

Angular Uncertainty

Table 4 lists the uncertainty in locating from the display, the angular location of the track relative to the host aircraft. The angular uncertainty is caused by the size of the symbol on the display. The aviator is assumed to be attempting to visually acquire the track from the display at the 5-km range.

Table 4

Angular Uncertainty in Degrees at 5 Kilometers

Display Area of Coverage (Kilometers)	Display Size (Inches) 3 x 3	5 x 5	7 x 7	9 x 9
30 x 30	21.23	12.83	9.20	7.17
80 x 80	53.10	33.37	24.17	18.90

Symbol Update Times

Table 5 shows the times between symbol updates on the display as a function of the relative speed of the aircraft being tracked, the area of coverage, and the display size. The table shows that a 180-knot track symbol would change position on the display once every 0.41 second to once every 8.50 seconds depending on the area of coverage and the display size and resolution. The update times are longer for slower tracks and show the uncertainty in determining from the display, the speed of the enemy track relative to the host aircraft.

Table 5

Symbol Update Times (in seconds)

(a) Display Coverage Area: 30 x 30 kilometers

Track Flight Speed (Knots)	Display Resolution (Lines/in)	Display Size (Inches)			
		3 x 3	5 x 5	7 x 7	9 x 9
30	35	18.43 s	11.06 s	7.89 s	6.14 s
	90	7.17 s	4.27 s	3.04 s	2.39 s
100	35	3.14 s	1.88 s	1.34 s	1.04 s
	90	1.22 s	0.72 s	0.52 s	0.41 s

(b) Display Coverage Area: 80 x 80 kilometers

Track Flight Speed (Knots)	Display Resolution (Lines/in)	Display Size (Inches)			
		3 x 3	5 x 5	7 x 7	9 x 9
30	35	49.29 s	29.56 s	21.09 s	16.43 s
	90	19.15 s	11.45 s	8.21 s	6.40 s
100	35	8.38 s	5.03 s	3.59 s	2.79 s
	90	3.25 s	1.95 s	1.39 s	1.09 s

To this point, the approach has been to define the preferred symbol size and establish two areas of coverage that were analysed in terms of display size and resolution. As can be seen, smaller areas of coverage presented on larger displays provide higher resolution information to the operator. With an 80-by-80-km area of coverage on a 3-by-3-inch display (35 lines/inch), the symbol covers 5 km, and the symbol update time for an aircraft traveling at 30 knots is almost 50 seconds, illustrating the dilemma of attempting to provide battlefield situation information within the constraints of existing aircraft panel and display space. The alerting and cueing information is somewhat imprecise. A solution to this potential problem is suggested in the next section.

AIR COMBAT DISPLAY CONCEPT

The information presented on the air combat display is the result of sensor data provided by the FAAD system. The FAAD system detects aircraft tracks, assigns identification numbers to the tracks, and classifies certain information about each track. The basic air combat display concept is shown in Figure 1. The display is a plan position indicator depicting radar-based information on a CRT. The concept borrows from air defense fire units and is modified to meet aviation requirements.

The display is designed as a 'heading-up' display. As the aircraft turns, the display rotates so that the heading of the own aircraft symbol is oriented toward the top of the screen. The number in the box at the top right-hand corner of the display shows the range, in kilometers, depicted on the display from the own aircraft symbol to the top of the screen. The ring represents the mid-range point (in this case, 10 km). In a final version of the display, the displayed range or area of coverage would be selected by the crew.

The own aircraft symbol is the cross located in the center of the display. Diamond-shaped symbols represent hostile aircraft, circles are friendly, and U-shaped symbols are unidentified or unknown aircraft. The symbols can be further modified to provide additional information. The symbol alone represents a fixed-wing aircraft. The symbol with a horizontal line across the top represents a rotary-wing aircraft. A single symbol indicates that the track consists of a single aircraft. A double symbol indicates that the track is a formation of multiple aircraft. The number at the lower right side of the symbol designates the assigned track number. The line extending outward from the center of the symbol shows the direction of movement of the track symbol.

Additional track information is available for presentation to the aircrew, but modifying the symbol to provide this additional information tends to clutter the display. To alleviate the potential for clutter, a track information line, presented in text, is available for each track and can be called up on the display by hooking the track (see Figure 2). Hooking is the term used for selecting or designating a given track. In current aircraft, hooking can be accomplished by entering the track number via a keypad.

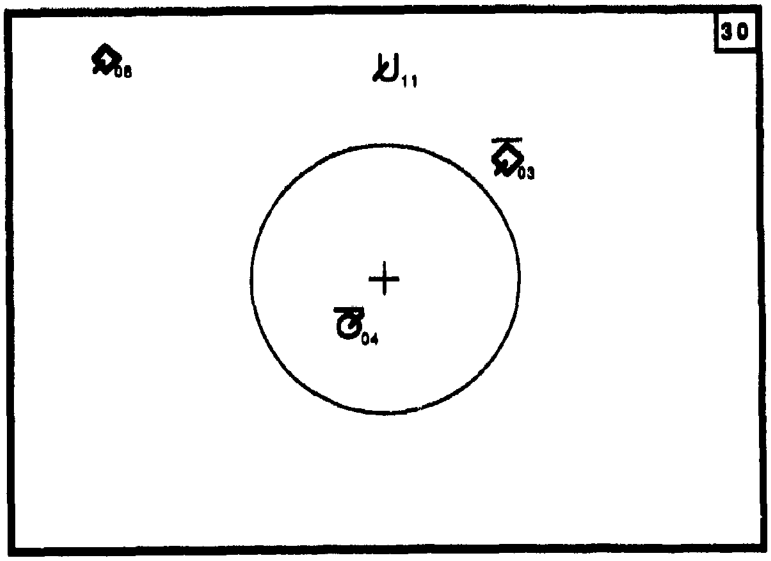

FIGURE 1. AIR COMBAT DISPLAY CONCEPT

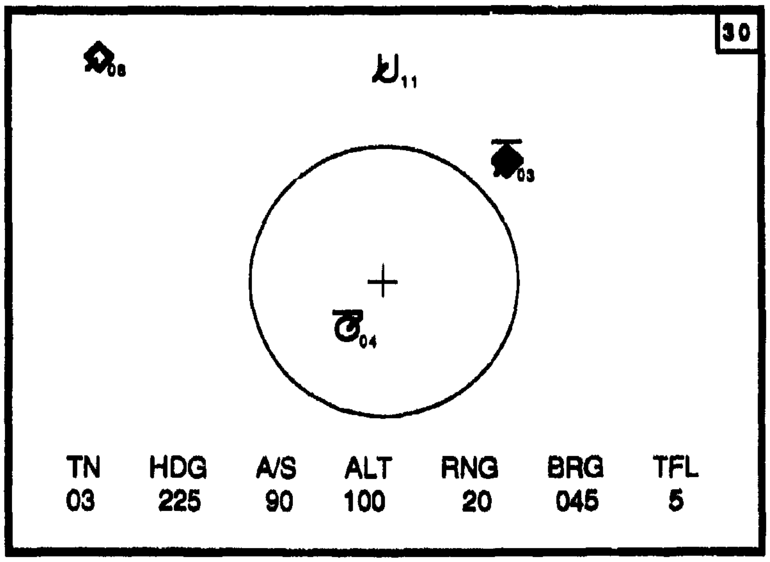

FIGURE 2. HOOKED TRACK AND TRACK INFORMATION LINE

Another very important reason for providing the track information line on the display is the impreciseness of the graphic track information resulting from the large area of coverage portrayed on small screens. The track information line allows more specific information about the track, (such as heading and relative location), to be presented than is possible with the graphic symbology. Information included in the track information line is track heading, airspeed, altitude, range and bearing from own aircraft to track, and time-to-first launch.

It appears that the graphic display is better suited for providing general situation awareness information while the text information line is better suited for providing specific or detailed information about a particular air track. When used in this manner, it is possible to present the air battle picture on a small screen with an adequate degree of utility.

DISCUSSION

This display concept is an initial design and successive iterations are evolving. Display capabilities are limited to the technology available in current Army helicopters. Display size is currently a limiting factor in providing a large area of coverage.

A primary challenge is attempting to depict an 80-by-80-km area of coverage on a nominal 3-by-3 inch display. As suggested by the preceding analysis, the air track data become somewhat imprecise. The requirement for an 80-by-80-km area is predicated on a hostile aircraft traveling at a high rate of speed and a friendly aircraft traveling at a very slow nap-of-the-earth speed. If display size was not an issue, this would be the best area of coverage for a maximum alerting and cueing distance. It has been suggested that the alerting of distant air threats be accomplished by a ground-based command post equipped with a large display screen, which would advise individual aircraft of impending air threats until in range of the aircraft's on-board display.

RECOMMENDED ENHANCEMENTS

As a concept new to Army aviation, much can be done to refine and enhance the air combat display. The following are some recommended areas for additional evaluation and analysis.

Saturation/Clutter of the Display

The number of air tracks that can be expected in a given 30-by-30-km or 80-by-80-km area is unknown. The number of air tracks will partly contribute to the saturation and clutter of the display. Even a small number of tracks, if close to each other, can create a cluttered situation in which symbols or symbol modifiers cannot be interpreted. However, it may be necessary to use techniques that will filter out some or all the following air track data. Ideally, these filters would be selected by the crew. The air track data that may require filtering are:

High altitude tracks
Fast moving tracks
Friendly tracks
Receding tracks
Tracks outside the area of interest

Analysis is required in this area to attempt to quantify the number of air tracks that may be anticipated in various segments of the battlefield and to assess display saturation and possible techniques for de-cluttering.

Track Information Line

Currently, the track information line includes all information available regarding the selected track. On a small display, there may not be enough space to present the entire line of information. Perhaps, the crew does not require all the information presented on the line. At any rate, an analysis of the track information line should be accomplished and the information most important and useful to the crew should be prioritized.

With prioritization, each type of information needs to be reviewed to determine the appropriate increment of presentation. For instance, to provide adequate cueing, should the bearing to track be provided to the nearest degree, 5 degrees or 10 degrees, etc? Track information line requirements must be coordinated with operational aviators who have experience with, or first-hand knowledge of, helicopter air combat operations.

Battlefield Geometry

Battlefield geometry such as division boundaries, air corridors, fire zones, and friendly fire unit locations are transmitted by the FAAD C^3I system. A determination must be made about how much, if any, of this information is useful to the helicopter crew. If battlefield geometry is to be provided, what effect is there on display saturation/clutter?

Soldier-Machine Interface

The soldier-machine interface issues require much more attention before the air combat display concept can be successfully integrated into an Army helicopter cockpit. The multiple functions on the CRTs create a complex and critical issue of identifying the specific crew inputs. This essential recognition is required to retrieve the appropriate information and change display functions quickly.

Audio and Speech Display Techniques

An evaluation needs to be made to determine the use of audio tones or speech synthesis as aids in alerting the crew of information on the screen. Such aids may be especially helpful, or even necessary, during periods of high visual task loading.

CONCLUSION

This report provides an account of the development of a display concept that alerts and cues Army helicopter crews to the location of friendly and hostile aircraft over the battlefield. The air track data to be displayed are generated by radar sensors and transmitted by the FAAD C^3I system. The concept borrows from air defense fire units and the symbology is found in DoD-STD-1477 (Department of Defense, 1983).

The area of coverage presented on the display was an important consideration in making the display a useful tool for alerting and cueing and, therefore, received considerable attention. Although the mission analysis shows that an 80-by-80-km area of coverage is best for providing timely alerting and cueing, it appears that the symbol coverage and symbol update rates associated with this area of coverage result in information that is not of sufficient preciseness when depicted on small display screens.

As an evolving concept, further analyses are required to arrive at a final design that will provide effective alerting and cueing in support of Army aviation air combat operations.

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DESIGNATION D'OBJECTIFS SOUS FACTEUR DE CHARGE : INTERET ET LIMITES DU VISEUR DE CASQUE.

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RESUME

Les viseurs de casque sont actuellement considérés comme l'une des approches possibles pour améliorer la conscience de la situation des pilotes de combat. Les avantages potentiels de ce type d'équipement peuvent cependant être diminués du fait des contraintes d'environnement aéronautique, comme les accélérations + Gz du combat Air-Air.

Une étude expérimentale en centrifugeuse a été conduite pour tenter d'évaluer l'impact des accélérations + Gz sur la fonction de désignation du viseur de casque.

Les résultats montrent que jusqu'à + 5 Gz la dégradation des performances de poursuite sous facteur de charge demeure modérée. Certaines limites des viseurs de casque apparaissent cependant. Elles sont essentiellement liées aux caractéristiques biomécaniques et aux modes fonctionnels de la coordination oeil-tête.

1. - INTRODUCTION

La plupart des grands programmes actuels d'avions de combat prévoient l'utilisation de viseurs de casque, en complément des visualisations classiques.

L'idée du viseur de casque n'est en fait pas totalement nouvelle puisque certains avions de combat en sont déjà dotés, parfois de longue date comme le VTAS en service sur les F4-J de l'U.S. Navy.

En France les premières évaluations du viseur de casque pour les avions de combat ont été menées dans le courant des années 70. A cette époque, dans le contexte de systèmes d'armes essentiellement secteur arrière, les études en simulation de combat n'avaient pas permis de conclure à l'intérêt de ce mode de désignation en combat aérien Air-Air. En revanche, des développements ultérieurs ont été menés avec succès pour les hélicoptères de combat, concrétisés au niveau du programme Franco-Allemand HAP-HAC.

Les progrès réalisés en matière d'optronique et les performances actuelles des missiles ont radicalement changé la situation et le programme ACT contient dès l'origine toutes les provisions nécessaires pour l'emploi d'un viseur de casque.

Ceci nous amène à considérer un premier point :

l'intérêt d'équipements comme le viseur de casque est étroitement dépendant des caractéristiques du système d'armes auquel il est intégré.

Les systèmes d'Armes des avions modernes sont devenus si efficaces que, paradoxalement, on peut craindre de voir augmenter d'une manière considérable la probabilité de destruction mutuelle des appareils engagés dans un combat (ni vainqueur, ni vaincu).

A ce niveau, le viseur de casque constitue l'un des moyens possibles pour faire pencher la balance. Le facteur humain reprend donc ici toute sa signification.

Les études d'emploi tactique, qui ont été menées en France sur ce sujet ont bien montré les nombreuses difficultés qui résident dans l'interprétation des résultats obtenus. Les problèmes d'homogénéité dans la population des pilotes amène à la conclusion générale que, quelles que soient les conditions du combat, les pilotes d'exception, ceux qui sont naturellement le plus conscient de la situation, arrivent à prendre le dessus.

En revanche, l'utilisation du viseur de casque est pour l'ensemble de la population la source d'un avantage certain. Vu sous un angle négatif, on peut aussi considérer que la non-possession de cet équipement entraîne un désavantage.

Ce dernier point contribue sans doute à établir l'idée que les viseurs de casque vont s'inscrire parmi les équipements incontournables pour les avions de combat des années à venir.

L'utilisation de ces équipements, en particulier lors de combat Air-Air, pose toutefois des problèmes auxquels les études en simulateur de combat ne peuvent répondre. Ce sont essentiellement les aspects liés aux contraintes biodynamiques résultant des évolutions de l'avion. Ces contraintes, qu'il s'agisse des vibrations ou des accélérations + Gz soutenues, affectent les deux fonctions du viseur de casque, désignation d'objectifs et présentation d'informations.

Ces dernières années le Laboratoire de Médecine Aérospatiale s'est particulièrement intéressé à l'impact des accélérations + Gz sur la fonction de désignation des viseurs de casque. Avant d'aborder ce point particulier, nous effectuerons un bref rappel des avantages présentés par le viseur de casque en terme de conscience de la situation ainsi que des principaux problèmes qui résultent de son emploi.

2. - VISEUR DE CASQUE ET CONSCIENCE DE LA SITUATION : AVANTAGES ET INCONVENIENTS.

La possibilité de piloter "la tête hors du cockpit" dans les conditions critiques (basse altitude, grande vitesse, combat), tout en conservant les informations sur le pilotage et la conduite des systèmes constitue un avantage fondamental pour le maintien de la conscience de la situation (2). Les viseurs collimatés tête-haute, liés à la structure de l'avion, donnent cette possibilité, mais seulement dans une zone restreinte à quelques dizaines de degrés. Cette zône, liée d'une manière générale au vecteur vitesse de l'avion, représente un intérêt fondamental pour certaines phases de vol. Par contre, dans le cas du combat Air-Air, les zones d'intérêt du pilote peuvent se trouver très éloignées du viseur central tête haute.

Pour HOLLISTER et coll. (4) le viseur de casque (HMS/D) fournit au pilote trois avantages principaux :

- Une visualisation de secours des informations présentées en tête-basse ou en tête-haute, quel que soit l'endroit où regarde le pilote.

- La possibilité de désigner des objectifs pour le système d'armes.

- Une visualisation du type tête haute mobile capable de présenter toutes les informations nécessaires à l'attaque et à la destruction de cibles au sol ou en vol.

SHERMAN (6) souligne que le viseur de casque représente également une solution pour la présentation d'informations lorsque le siège du pilote est très incliné.

Dans tous les cas ces avantages ne peuvent être considérés comme effectifs, surtout pour les avions de combat, que si l'encombrement et la masse des équipements demeurent compatibles avec les contraintes biodynamiques du vol.

L'effet de ces contraintes au cours du vol grande vitesse, basse altitude a été rapporté, tant pour ce qui concerne la fonction de désignation (7) que celle de présentation d'informations visuelles (3). Lors d'études en laboratoire confirmées par des essais en vol, TATHAM a montré que seules les composantes basse fréquence (inférieures à 4 Hz) affectaient la précision de visée. En utilisant une méthodologie identique, JARRET montrait que la lisibilité du viseur sous vibration pouvait être améliorée en augmentant le contraste lumineux.

Les problèmes posés par les évolutions du combat Air-Air dans le domaine visuel sont loin d'avoir été aussi bien étudiés que ceux résultant des vols tactiques. L'étude expérimentale que nous présentons a pour objet d'apporter quelques éléments dans ce domaine.

3. - METHODES

L'étude a été menée sur la centrifugeuse du Laboratoire de Médecine Aérospatiale du Centre d'Essais en Vol de BRETIGNY sur Orge.

3.1. - Dispositif Expérimental

3.1.1. - Plateforme d'expérience

Une maquette géométrique du démonstrateur Rafale, articulée autour d'un siège incliné à 32° a été utilisée pour les essais. Cette maquette a été installée dans la nacelle universelle de la centrifugeuse qui permet d'accueillir des expérimentations encombrantes. Des essais de validations ont ensuite été menés sur une maquette du prototype ACT (siège incliné à 29°).

La commande de pilotage située sur la banquette droite comporte un interrupteur permettant au pilote de valider les évènements. Une visualisation centrale sur un moniteur vidéo est utilisée pour présenter au pilote des informations sur le déroulement des essais et les résultats obtenus. Une valve anti-G permet l'alimentation de l'équipement de protection porté par le pilote. Enfin, un trièdre d'accéléromètres placés près de la tête du pilote permet la mesure des trois composantes d'accélération Jx, Jy, Jz.

3.1.2. - Dispositif de présentation de cible

Un dispositif optique à 2 degrés de liberté mû par des moteurs asservis, projette un rayon Laser He-Ne sur un écran hémisphérique de 170 cm de diamètre. Cet écran est approximativement centré sur la position de la tête du pilote. L'amplitude de déplacement autorisée par le système est de ± 160 degrés en gisement et + 90 en site. Les vitesses de déplacement peuvent atteindre 700°/s en gisement et 2000°/s en site.La précision de positionnement de la cible est de 12 minutes d'angle. Une recopie de la position angulaire du miroir de sortie, en site et en gisement, est utilisée pour déterminer la position de la cible dans le repère de la cabine.

3.1.3. - Dispositif de mesure de la position de la tête

Le viseur de casque électro-optique THOMSON-CSF est utilisé pour déterminer la position de la tête et l'orientation de la ligne de visée du pilote. La précision de ce système est meilleure que 0,5° pour les angles et que 1 mm pour les translations. La cadence d'échantillonnage réelle est de 20 Hz. Ce système comporte deux triangles de diodes émettrices et un viseur collimaté, intégré dans un casque GUENEAU 458 modifié par les soins du Laboratoire. La masse du casque équipé est de 1380 g. Les capteurs sont constitués par deux barettes CCD disposées de part et d'autre de la tête du pilote sur un support indéformable. Dans la disposition utilisée lors des essais le champ de mesure couvrait approximativement + 60° en gisement et + 60° en site.

3.1.4. - Système informatique d'acquisition

La gestion des expérimentations, la commande du dispositif optique et l'acquisition des données sont assurées par un calculateur DEC LSI 11-73. Les programmes d'application sont écrits en Fortran IV avec des routines Assembleur. Ces programmes fonctionnent sous un système d'exploitation RT-11-SJ.

3.2. - <u>Protocole</u>

3.2.1. - Sujets

Six sujets volontaires exempts d'affections pathologiques évolutives (Age 23-43) ont participé à l'expérimentation. Ils ont été recrutés parmi les personnels du Centre d'Essais en Vol et tout particulièrement au sein de la section des parachutistes d'essais. Tous les sujets avaient une expérience préalable de la centrifugeuse. Ils étaient, en règle générale, résistants aux effets des accélérations de Coriolis. Lorsque ce n'était pas le cas une prophylaxie anti-naupathique a été utilisée. Une deuxième expérimentation a été menée ultérieurement avec deux pilotes de chasse. Elle avait pour but de valider quelques points précis des premiers essais.

3.2.2. - Conditions expérimentales

Chaque sujet a effectué un total de six lancements comportant chacun trois montées en accélération. Le nombre total d'essais a été déterminé par la combinaison des conditions d'accélération et des différentes trajectoires de cibles présentées. Avant chaque lancement, une acquisition de référence à 1 G était effectuée pour chacune des trajectoires étudiées. Dans tous les cas, la position initiale de la cible et la trajectoire suivie étaient totalement prédictibles.

3.2.2.1. - Trajectoires

Trois trajectoires ont été utilisées pendant les essais. La durée de chaque trajectoire est de 10 secondes.

La trajectoire n° 1 se compose de 2 segments : le premier part de + 50° en site et - 50° en gisement ; la cible se déplaçant jusqu'à un point 30°

en site, 0° en gisement avec une vitesse de 3°/s en site et 8°/s en gisement. Le deuxième segment est purement vertical, à 7°/s jusqu'au point de référence 0°.

La trajectoire n° 2 est sortante. La cible démarre à - 20° en gisement, + 20° en site et se déplace à 3°/s en site et 7°/s en gisement vers un point + 50° en site + 50° en gisement.

La trajectoire n° 3 est rentrante, purement dans le plan vertical. La cible démarre à + 55° en site et se déplace à 5,5°/s jusqu'au point 0°.

3.2.2.2. - Conditions d'accélérations

Les essais ont été menés pour deux sous-protocoles, Palier et Transition.

Dans le premier cas la poursuite de la cible est effectuée avec un niveau constant d'accélération + Gz (3, 4 ou 5 G), installé avec une variation de 0,6 G/s.

Le protocole Transition étudie la poursuite lorsque l'accélération varie de 1,4 G résultant à 5 G résultant avec des pentes de 0,2, 0,4 et 0,6 G/s.

3.2.2.3. - Plan expérimental

Le protocole Palier a toujours été réalisé avant le protocole Transition. Pour éviter un effet lié à l'ordre de présentation des essais, les différentes combinaisons d'accélération et de trajectoire ont été réparties en effectuant une permutation circulaire.

3.3. - Traitement des données

Les données ont été exploitées au moyen d'un logiciel de traitement spécifique comportant des fonctions interactives.

Les paramètres étudiés ont porté sur l'acquisition des cibles (vitesse, durée) et sur les caractéristiques de la poursuite Ecart moyen et Ecart quadratique moyen (E.Q.M.).

4. - RESULTATS

Les résultats présentés ici portent essentiellement sur les caractéristiques de poursuite de cibles après qu'elles aient été acquises. Nous distinguerons deux aspects : l'un qualitatif, l'autre quantitatif.

4.1. - Aspect qualitatif des poursuites

Dans l'ensemble, les sujets n'ont pas rencontré de difficultés particulières au cours des différentes poursuites. Il existe une très grande variabilité au niveau interindividuel dans la qualité de la réalisation de la tâche. Alors que certains sujets arrivent à maintenir une qualité de poursuite à un très bon niveau dans tout le domaine étudié (fig.1A), d'autres n'obtiennent que des résultats relativement médiocres (fig.1B).

Sur le plan qualitatif deux points attirent particulièrement l'attention. Le premier concerne la trajectoire n°1, le second la trajectoire sortante n°2. La trajectoire n°3, en revanche, n'appelle ici pas de commentaires particuliers.

4.1.1. - Effet d'un changement de direction

La trajectoire n°1 comporte un changement de direction relativement brutal. Bien que celui-ci soit parfaitement prédictible, on observe assez fréquemment à ce moment un décrochage de visée, avec des écarts instantanés qui peuvent atteindre cinq à dix degrés.

La figure 2 illustre bien ce phénomène qui, sans être totalement répétitif, est très souvent présent à des degrés divers.

4.1.2. - Trajectoire sortante

La trajectoire sortante a globalement été jugée comme la plus difficile à poursuivre, même pour les pilotes de chasse. Ceci est particulièrement vrai pour le protocole Transition, où l'accélération terminale est toujours de 5 G. Cette accélération terminale coïncide dans ce cas avec l'excentricité la plus forte de la cible 50° en site et en gisement. Alors que l'atteinte de cette excentricité ne pose jamais de problème lors de ces acquisitions, on observe très fréquemment un blocage de la tête lors de la poursuite. Un exemple de ce type de blocage, résultant en une perte rapide de la visée est présenté à la figure 3.

4.2. - Aspects quantitatifs

Les résultats obtenus, présentés en terme d'écart quadratique moyen de poursuite, ont été rassemblés pour les différentes configurations d'accélération dans les figures 4 à 7. Il s'agit là de valeurs moyennes obtenues sur 6 sujets. On note très peu de variation pour les valeurs d'EQM en gisement, à l'exception de la trajectoire 1 (fig.5). Dans ce dernier cas les valeurs d'EQM qui, en règle générale, sont proches de 1 degré atteignent 1,30 à 0,6 G/s.

En revanche, pour ce qui concerne les valeurs observées en site, on relève des variations plus importantes pour les trajectoires. Globalement, les poursuites effectuées à 3 et 4 G ne présentent que peu de différence avec les résultats de référence. Les valeurs moyennes observées à 5 G sont sensiblement plus élevées pour la trajectoire 2 où elle atteint, 1,3°. Comme pour les résultats obtenus avec des cibles stationnaires (5) ce sont les variations d'accélération qui engendrent les E.Q.M. les plus importants. Ceux ci dépassent généralement 1,2° dès 0,4 G/s pour atteindre 1,8° à 0,6 G/s pour la trajectoire 2 (fig.6).

5. - DISCUSSION

Dans sa fonction de désignation d'objectif, le viseur de casque ne peut contribuer correctement à l'amélioration de la "conscience de la situation" que dans la mesure où la difficulté de sa mise en oeuvre n'obère pas les avantages qu'il apporte par ailleurs.

A ce titre, les résultats obtenus en centrifugeuse montrent assez clairement que, dans le domaine d'accélération considéré, la dégradation des performances de poursuite demeure relativement modérée. Encore faut-il que ces performances soient compatibles avec les caractéristiques des armements employés. Notons ici que les résultats ont été exprimés en terme d'écart quadratique, paramètre classiquement utilisé pour évaluer la performance, mais que les valeurs extrêmes de l'écart instantané peuvent être beaucoup plus importantes.

On peut considérer que ces écarts s'accroissent systématiquement à partir de 3 G et pour des taux de variation supérieurs à 0,4 G/s.

Les résultats qualitatifs obtenus avec le changement de direction de la trajectoire 1 montrent assez bien les limites d'une poursuite avec un réticule lié à la tête. Il ne faut en effet pas oublier que ces trajectoires étaient totalement prédictibles. On peut donc penser qu'un avion capable d'effectuer un changement rapide de l'orientation de son vecteur vitesse poserait des problèmes aussi bien avec un viseur de casque qu'avec les moyens classiques de désignation.

De même les résultats obtenus avec les trajectoires sortantes donnent matière à réflexion. Il est en effet surprenant de constater que, lors d'acquisitions rapides, des cibles excentrées à 50° en site et en gisement sont généralement atteintes sans problème.

La limitation observée dans la partie terminale de la poursuite d'une cible évoluant lentement est sans doute liée à l'inclinaison du siège et de l'appui-tête. Si cette inclinaison est globalement favorable à l'acquisition de cibles évoluant à fort site, elle semble ici poser un problème de mobilité. Pourtant la poursuite de cibles sortantes constitue très certainement une configuration de combat tout à fait possible, surtout dans des conditions de combat du type "deux contre plus de deux".

Cette problématique de combat multicible à courte distance constitue très certainement un point d'intérêt pour les viseurs de casques. Les acquisitions effectuées montrent que le déplacement d'un point à un autre, même sous facteur de charge est réalisé avec une précision relativement bonne, à condition d'avoir une idée précise de la localisation du point d'arrivée (cibles prédictibles). Au cas où cette information de localisation serait fournie au moyen d'une figuration viseur, il conviendrait donc de s'assurer que celle-ci conduise bien à une évaluation précise du déplacement angulaire à effectuer. Rappelons ici que, par définition, les mouvements balistiques ne peuvent être interrompus par une boucle de rétroaction. En fait, on observe assez fréquemment des dépassements d'objectifs, suivis de rattrapages qui ne peuvent qu'être préjudiciables à une conscience de la situation optimale.

Enfin, pour clore ce chapitre et ainsi que le souligne BARNES (1), le viseur de casque fait appel à une action "non naturelle", dans la mesure où il va à l'encontre des mécanismes de couplage oeil-tête. Cette limitation physiologique inhérente au principe du viseur de casque incite donc à poursuivre les efforts en matière d'utilisation du regard plutôt que de la tête.

6. - CONCLUSION

Pour de nombreux auteurs, le viseur de casque constitue un moyen d'améliorer la conscience de la situation du pilote de combat.

A côté d'avantages évidents, on conçoit bien que l'utilisation d'un système lié à la tête puisse, du fait des accélérations rencontrées au combat, perdre une partie de son efficacité.

Les expérimentations menées en centrifugeuse ont permis de mettre en évidence certains points qui peuvent constituer une limite d'emploi de ce type de système. Sur le plan quantitatif, la dégradation des performances de poursuite reste relativement modérée. Cette dégradation est plus sensible lorsque l'accélération varie avec des taux élevés que lors de poursuite avec une accélération + Gz établie.

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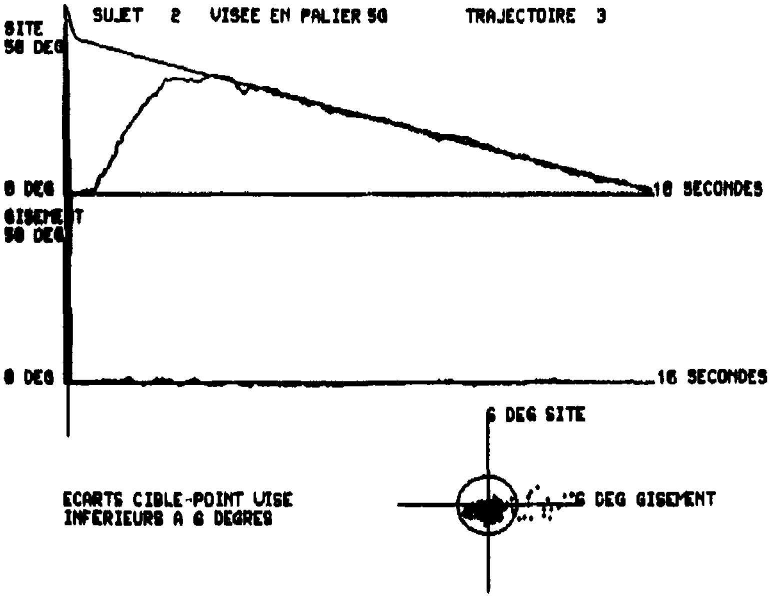

FIG.1.A : Résultats bruts : pour une trajectoire 3 on constate d'excellents résultats pour une poursuite au cours d'un plateau d'accélération à + 5 Gs.

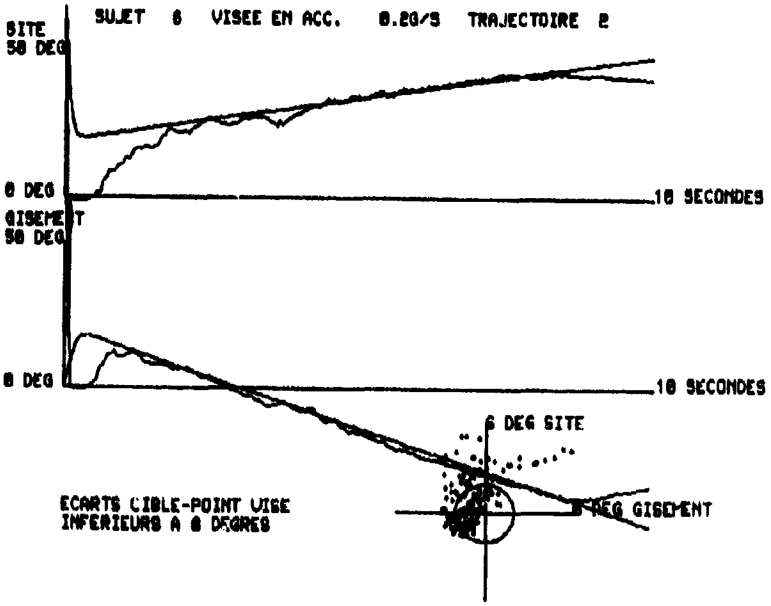

FIG.1.B : Résultats bruts : les résultats obtenus ici montrent une dispersion beaucoup plus importante de la visée.

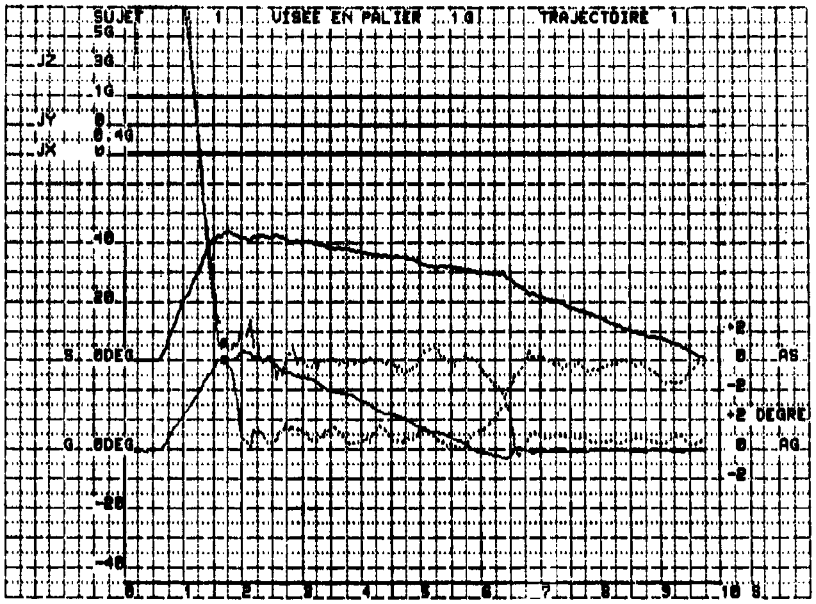

FIG.2 : On note ici, pour la trajectoire 1 une augmentation importante des écarts instantanés lorsque la cible change de direction.

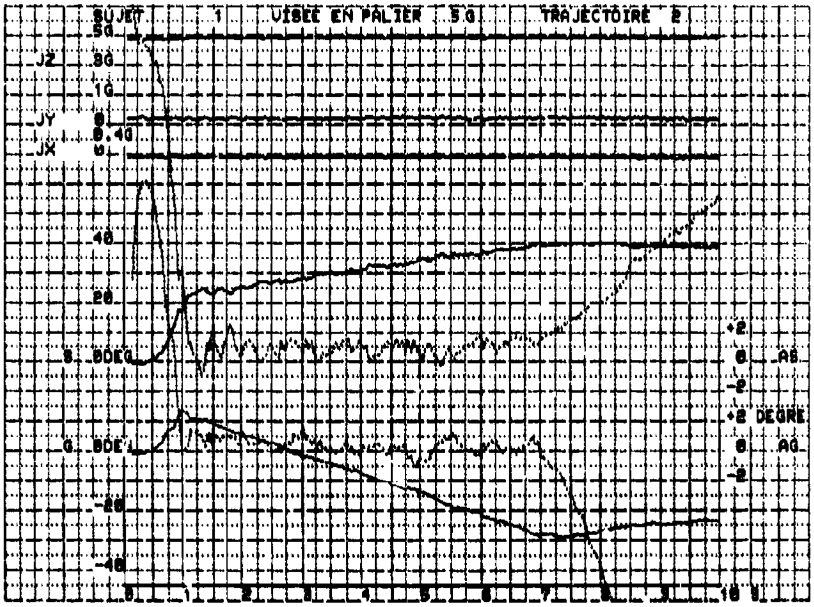

FIG.3 : Effet d'une trajectoire sortante. La tête est bloquée à 40° en site et 20° en gisement.

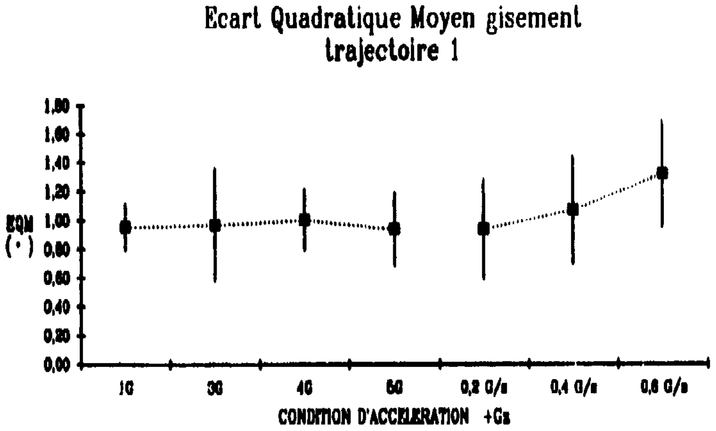
Ecart Quadratique Moyen gisement
trajectoire 1

FIG.4 : On note pour la trajectoire 1 une légère augmentation de l'EQM pour les visées à 0,6 G/s.

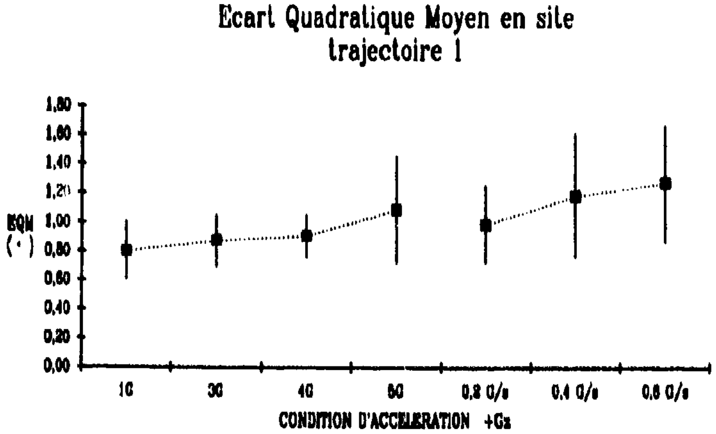
Ecart Quadratique Moyen en site
trajectoire 1

FIG.5 : Valeurs moyennes de l'EQM en fonction des différentes conditions d'accélération + Gz pour la trajectoire 1.

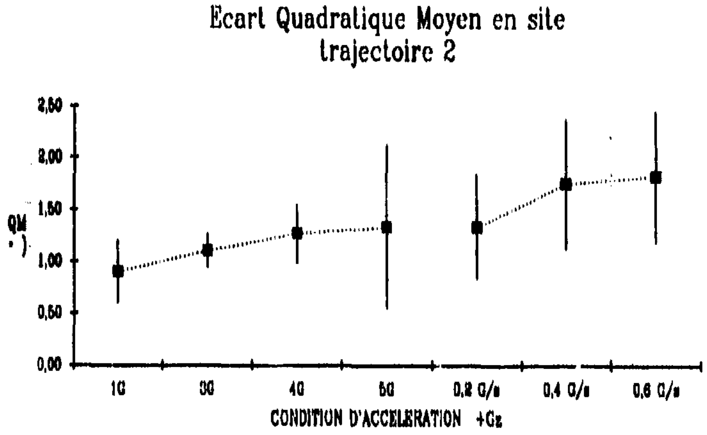
Ecart Quadratique Moyen en site
trajectoire 2

FIG. 6 : Valeurs moyennes de l'EQM en fonction des différentes conditions d'accélération + Gz pour la trajectoire 2.

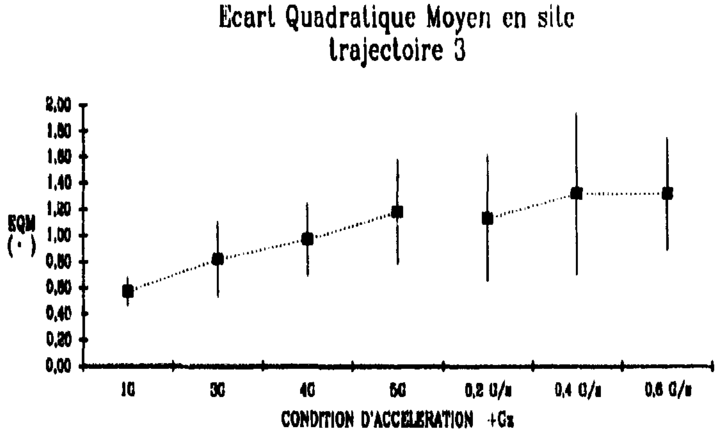
Ecart Quadratique Moyen en site
trajectoire 3

FIG. 7 : Valeurs moyennes de l'EQM en fonction des différentes conditions d'accélération + Gz pour la trajectoire 3.

THE SIMULATION OF LOCALIZED SOUNDS FOR IMPROVED SITUATIONAL AWARENESS

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It is argued that, in everyday life, the directional information available in sounds is automatically incorporated into the listener's overall awareness of the situation. The absence of such cues in the air-borne environment must inevitably impoverish the data base from which the pilot builds his appreciation of the situation. Experiments are reported, which indicate that modifying cockpit sounds, to give them a synthetic directional quality, would indeed facilitate spatial appreciation.

INTRODUCTION

Much of the enhancement of a pilot's awareness of his situation is attempted by supplementing the information from his own senses, with that derived from 'artificial' senses, such as radar. However, while efforts are being made to give pilots more than five senses, there seems to be a certain amount of neglect of one of the originals - the sense of hearing. The neglect is not of course complete, since auditory warnings have been developed (*eg* 1), and Direct Voice Output (DVO) may be expected to become increasingly important. Nevertheless, if developments were confined to these areas it could be argued that the restriction would be analogous to constraining pilots to use their eyes solely to watch flat screens: in each case spatial appreciation is rendered if not impossible, at least very difficult. This paper will therefore report upon some preliminary investigations into the feasibility of employing stereo sound in the cockpit. With positive results, the ultimate goal would be for all signals passed to a pilot's headphones to be given a directional quality. In this way, warning sounds would indicate the direction of the threat, and radio messages from a wing-man could appear to originate from the appropriate location.

The advantages of using 'three-dimensional' sound cannot be taken for granted. However precisely the required auditory characteristics are synthesised (which is itself a problem, to be addressed later), the resulting signal cannot be without a degree of artificiality, since directional sounds, such as warnings, are not naturally present in the cockpit (2). Whereas the directional information of a sound in an earth-bound situation will be readily integrated into the overall cognitive analysis of the situation, the same may not be true for inappropriately incorporated air-borne sounds. This possible difficulty may, however, serve as an indication of the potential value of localizable sounds. Just as they are in a sense artificial, so too is much of the visual information presented to the pilot. Apart from his direct view of the world (which may also be removed if cockpits ever become enclosed), the rest of his knowledge is derived from characters and symbols, displayed on screens. Incorporating this information into a general awareness of a situation of course encounters the same problems as those postulated above, for artificial sound. Part of the difficulty lies in the need to translate from a screen to the real world, but a further problem is the lack of redundancy. I do not refer to redundancy within one modality, for that can be added with colour, shape, size and so on. The redundancy which is missing is inter-modal, or between the senses. In everyday situations it is the norm for sight and hearing to provide complementary information about events and, as is the nature of redundancy, it is likely that the combined information leads to faster responses than would be triggered by either stimulus alone. Consequently, it is worth considering that in the cockpit, although both visual displays and stereo sound have their weaknesses, together they may significantly enhance the assimilation of information. The first experiment to be reported examined the extent of any interaction between inter-modal spatial information.

EXPERIMENT I

If it is contemplated to use stereo sound, as an enhancement to visually presented spatial information, then it must be demonstrated that the audio material is readily analysed, along with the visual counterpart. A useful evaluation technique for such a situation involves the application of the Stroop effect (3). In its usual form, the Stroop effect is demonstrated by asking a subject to name, as quickly as possible, the sequence of coloured inks used to write a list of words. This is not generally a very difficult task, unless the words themselves are colour names, not matching the inks in which they are written. In that situation the subject's response rate is slowed, and there is a considerably greater error rate. In attempting this exercise, the subject is, of course, trying to *avoid* assimilating the textual information: it is not relevant to the task requirements and only serves to make the activity more difficult. Nevertheless, the obvious confusion suffered by the subject provides clear evidence that the words *are* being read. Although the precise mechanisms underlying the confusion are still a matter for debate (*eg* 4, 5), Naish (6) has shown that a lack of complete understanding does not preclude the use of the effect, as a tool in other investigations. The rationale behind using the Stroop effect in this way is as follows: If a source of information can be shown to interfere with responses to other, simultaneously presented information, then the interfering material must have been receiving analysis. Moreover, since it may be presumed that subjects will have attempted to avoid the interference, it must be accepted that the analysis was automatic. It follows that, if it is not possible to ignore information when it is damaging, then it will certainly also be processed when it is potentially useful.

This principle was employed in the first experiment. A more detailed description of the methodology, together with a complete analysis of the results, will be presented elsewhere. In the present paper, sufficient details will be given to make the technique and the relevant results clear.

Method

Subjects were required to respond to a series of composite stimuli, generated by a computer, which also monitored and timed subject responses. Each stimulus incorporated the concepts of LEFT, RIGHT and CENTRE, presented in four different ways. On each trial, one of these words was displayed upon the computer vdu, appearing either in the centre of the screen, to the left, or to the right. Simultaneously with this visual presentation, subjects heard one of the words left, right or centre, spoken over stereo headphones. (The voice was recorded as digitised speech, stored in computer memory and replayed via a digital-to-analogue converter.) The speech was also presented so as to seem to come from the left, the right, or the centre. During a sequence of trials, all possible combinations of these four attributes were presented to subjects. Consequently, in some cases the composite was entirely congruent, *ie* the text, its position on the screen, the spoken word and its perceived location all conveyed the same concept. On other occasions, one or more of the components of the stimulus could disagree.

For each trial the subject was given a cue, displayed on the computer screen, indicating to which of the four aspects of the stimulus the attention was to be directed. The subject's response was made by pressing one of three touch pads, placed in a row and corresponding to LEFT, CENTRE and RIGHT. Thus, for example, on a particular trial the subject might be given the cue TEXT, and be presented with the word 'right', printed to the left of the screen, while hearing the word 'centre' in the right ear. The cue would direct the subject to respond on the basis of the printed word, and hence to press the right hand button. In this example, the auditory location (although not the spoken word) would agree with the selection of 'right', so that one other attribute was congruent with the target. In general, 3, 2, 1 or 0 other attributes could agree with the required response.

Results

It was reasonable to expect that the extent of the congruency between a target attribute and the remaining three components of a stimulus would affect response times. Figure 1 summarises results, which are the mean reaction times of eight subjects, to stimuli of increasing degree of mismatch. As can be seen, the expected trend is largely present and Page's L Test shows it to be statistically significant ($p = 0.05$). Clearly, complete congruency between stimulus components (*ie* all three non-target attributes congruent with the target) leads to the fastest response times. Even the presence of a single mismatching component produces a marked slowing. Responses are still further delayed, if only one or no other components agree with the target, although these two situations seem to produce equally slow reactions.

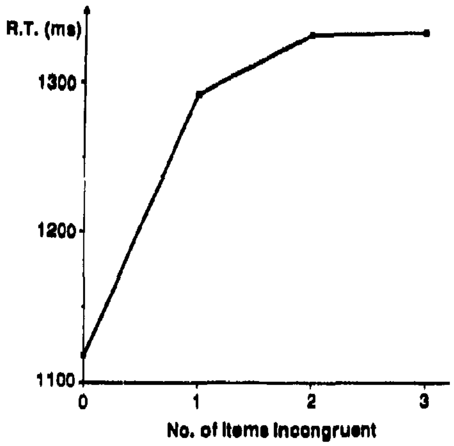

Figure 1 Effects of increasing incongruency upon reaction times

The above results demonstrated that a single incongruent element within the composite stimulus would impair response times. Since attention tends to be directed to a modality, it was predicted that the single mismatch would be most damaging when occurring in the same modality as the target. For example, suppose a subject were instructed to respond on the basis of the spoken word. It would then be plausible to suppose that an incongruent location by ear would be more damaging than either a mismatching screen location or printed word. The prediction was supported, with mean response times to same modality mismatches being 128 ms longer than mismatches in the other modality. The difference was significant ($p < 0.025$, 1-Tailed).

Discussion

The results are a strong indication of the desirability of representing spatial information by combining as many congruent stimulus attributes as possible. This is not unexpected, since, as was pointed out in the Introduction, it is the normal earth-bound experience for visual and auditory information to convey the same 'message'. Perhaps of more interest is the finding that a failure to deliver congruent information is most damaging when the mismatch occurs in the target modality. The implication of this is that responses to auditory signals in a cockpit would be significantly faster, if the sounds also conveyed an appropriate directional sensation.

Having concluded that there are potential benefits to be derived from the use of localizable sounds, attention must now be turned to the question of how such sounds should be produced. At first, this may seem a relatively trivial problem, since there is no reason why a pilot wearing headphones should not receive a stereo pair, rather than an identical mono signal to each ear. However, the directional characteristics would have to be synthesized, since auditory warnings and messages in the cockpit environment are not intrinsically localizable. Warning sounds could in principle be recorded in stereo, for play-back when required, but a problem would arise when the pilot turned his head. Since the sound source should seem to stand still, it would be necessary to modify the signal, to represent a new direction in relation to the head. The required head position sensing is achievable, but are a multitude of recordings, for every possible head angle, a feasible option? Even if the answer were "Yes", it would not be a technique that could be used for radio messages, which, being unpredictable, could not be pre-recorded. Since the only viable approach would seem to be to synthesize the correct sound characteristics, it is necessary to examine the precise nature of the direction signature carried by natural sounds, and which it would be hoped to reproduce.

Auditory localization cues

The nature of the cues which enable the direction of a sound source to be perceived have been the subject of research for a considerable time (7). Good accounts have been published of the mechanisms involved (see for example 8), and only a brief explanation will be given here.

The brain utilises two classes of information, which the ears extract from a sound: temporal and spectral. Figure 2 represents sound waves approaching a listener from front right. It will be seen that, when the sound first started, the vibrations of the air must have reached the right ear before the left. The size of the timing disparity will depend upon the source/head angle, and for sounds directly to one side of the head the delay to the distant ear is of the order of 700 μs. It is also apparent that, as well as the time difference at the start of a sound, the same disparity is continually reflected in the phase difference between the two ears. Hence, at the moment represented in the Figure, the right ear is experiencing a maximum in air pressure (a wave crest), while for the left that particular crest is yet to arrive. The brain uses such phase differences for direction estimation, although it only does so for sounds with frequencies lower than approximately 1500 Hz. This restriction arises, since at high frequencies the spacing between wave crests is less than that between the ears, so a given phase difference could be produced by more than one sound direction. The lack of sensitivity to phase at shorter wavelengths thus avoids the problem of ambiguity.

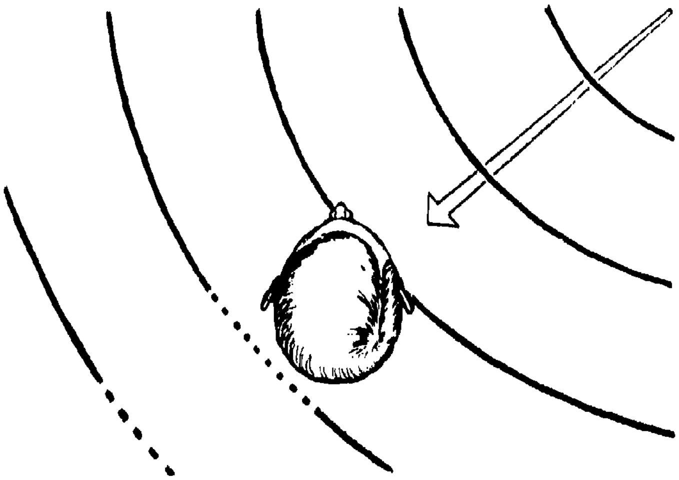

Figure 2 A representation of sound waves passing a listener

Although higher frequency sounds cannot supply useful phase information, they do give rise to inter-aural spectral differences. Figure 2 also represents the shadowing effect of the head, with sound waves to the left, away from the sound source, being of smaller amplitude. In other words, the left ear signals a quieter sound than the right. This intensity difference is also used by the brain, and interestingly, it complements the phase cue by becoming unavailable at wavelengths longer than the head width. This is because sound waves bend round obstacles smaller than their wavelength, so casting negligible shadows. Since most sounds (apart from pure tones) comprise a mixture of frequencies, the preferential shadowing of the higher frequency components gives rise to a difference between the overall spectra received by the two ears.

As well as the spectral effects of shadowing, the pinnae (ear flaps) cause more subtle modification of the received sounds: an effect also monitored and utilised by the brain. The way in which this effect is brought about is shown diagrammatically in Figure 3. Sound waves entering the ear may do so by passing directly down the auditory canal, or after reflection in the folds of the outer ear. Eventually, waves from the different routes join together, and will mutually interfere. The interference arises as a result of phase differences between the waves, caused by the different path lengths covered.

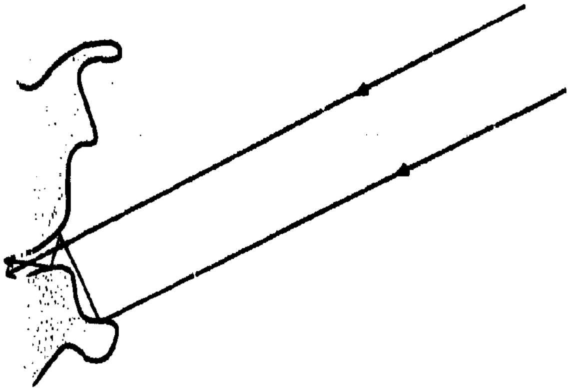

Figure 3 Section through pinna, showing direct and reflected waves

The resulting combined wave may be of high amplitude (loud), if the waves happen to end up in step, or may be effectively absent, if there is a half wavelength discrepancy. In a complex sound, of many frequencies, the net result is that some components will be received with much more intensity than others, but which ones are affected, and by how much, will depend upon the angle at which the incident waves strike the pinna. The process is directly analogous to the colouring of white light, when it is reflected simultaneously from the upper and lower surfaces of an oil film on a puddle.

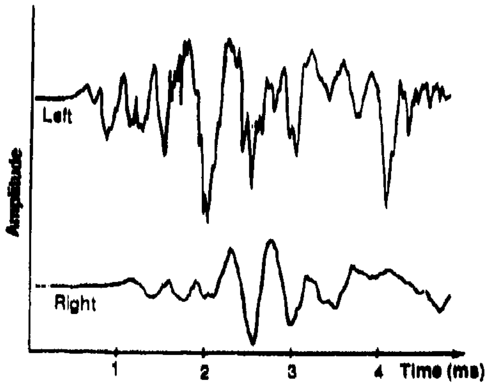

Figure 4 The sound of a 'clap', recorded at the left and right ears

Figure 4 reveals the combined effect of the mechanisms described. It shows the waveforms recorded in the left and right ears of a listener, when receiving the sound of a single hand clap. The sound originated from the front-left of the listener, and it will be seen that corresponding features in the two waves arrived earlier in the left channel. It is also clear that the overall amplitude at the more distant right ear was reduced, and that there is a particular reduction in the higher frequencies, revealed in the smoother outline of the right waveform.

The simulation of localization

An ideal simulation would attempt to synthesise all three of the above cues, for presentation to the listener, but they are not equally easy to generate and may not all be essential. The temporal disparities (onset times and phase differences) are the easiest to create, since it is only required to introduce a delay in the signal path to one or other ear. Of course, for real-time changes, the extent of the delay would have to vary with the simulated head/source angle, but modern digital techniques can readily achieve the desired effects. It is interesting to note that commercial recording companies avoid temporal differences between recorded stereo channels, since for play back via loudspeakers the timing effects would only be preserved for listeners sitting exactly midway between the speakers. Such recordings rely only upon the amplitude differences between the left and right channels. To simulate these amplitude differences is slightly less simple: overall amplitude changes are easily introduced, but it will be recalled that shadowing is most marked at the higher frequencies, so there is a need for selective, frequency dependent attenuation. The subtle colourations of the sound imparted by the ear flaps represent the greatest challenge to simulation. There would be a need to process left and right channels separately, passing each through a comb filter, with ever-shifting pass and stop bands. The temptation is that, if any cue is to be omitted, then this should be it. Unfortunately, the effects of the pinnae are important, and without their sound modifications, sources tend to be perceived as being lateralised inside the head, rather than appearing to exist at a point outside the observer (9, 10, 11). Nevertheless, since it seemed likely that even a rather unsophisticated stereo simulation would be better than none, it was decided that an initial exploration would not attempt to mimic pinnae effects. Moreover, the grosser spectral effects of head shadowing would only be represented relatively crudely. The precise nature of the sounds used, and the means of synthesising them, have been reported (12), but the significant features of the experiment are described below.

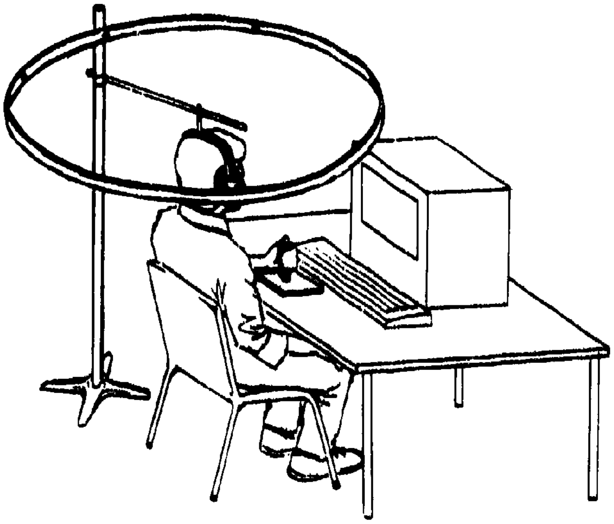

Figure 5 Arrangement of apparatus in Experiment II

EXPERIMENT II

Rationale

The experiment was designed to determine whether stereo warning sounds would elicit faster responses than simple, 'mono' sounds. Figure 5 conveys the nature of the set-up. Subjects sat at an Apple computer, which controlled the administration of a simple tracking task. The hoop, around the subject's head, supported eight, equally spaced light emitting diodes (LEDs), and from time to time, while the subject was tracking, an LED was turned on by the computer. Having detected this, the subject was required to enter the LED's number (1 to 8) on the computer keyboard. The time from switch on to entry was recorded automatically, and the LED was extinguished. The subject wore a pair of headphones, and a computer-generated warning sound could be delivered over the 'phones, when an LED was lit. These sounds could be given a synthetic directional quality, intended to convey the sensation of coming from the direction of the illuminated LED.

The sounds consisted of brief 'bleeps', comprising a range of frequencies. As in Experiment I, the signals to the two ears were independent, and were sent from the computer, via digital-to-analogue converters. It will be seen in Figure 5 that an arm is shown, connected to the headband of the subject's 'phones. This was a pivoted arm, which did not greatly impede the subject's movements, but supported a potentiometer, used to monitor head position. The computer used the direction-of-regard information to manipulate the sound, so that its direction would seem to be constant, even when the subject turned to find the LED. The phase characteristics of the sound changed smoothly with head movements. That is, the timing differences between the two ears faithfully emulated those to be expected from a real sound source. However, the changes in amplitude of the different components, such as would have occurred through head shadowing, were only made in rather coarse steps. Only eight digitised versions of the sounds had been stored, each with a different spectral composition. Consequently, instead of changing smoothly with head movements, the tonal quality of the sound could only be altered in discrete steps, every 22.5 degrees of head rotation.

Method

Subjects sat at the computer and, following instructions and initial practice, began to carry out the tracking task. This required the subject to use a joystick, in order to keep a cross in a moving square, on the computer vdu. Throughout the experimental period tracking performance was monitored. Once the subject had become familiar with the tracking, the first LED signal occurred. The choice of LED was random, each of the eight being used three times in a block of trials. Once the subject had extinguished the light, by typing its number (which was printed on the hoop, beside the LED), there followed a random interval of between 4 and 12 seconds, before the next LED was turned on. Tracking continued during the inter stimulus intervals. Three types of trial block were used: with no warning sounds, with centralised bleeps, or with localized warnings. In the case of the central bleeps, the two ears received identical signals, which did not change with head angle. Subjects were informed prior to a block whether sounds would be used, and in the localized condition were told that the bleeps may seem to come from the light direction. The order in which the three conditions were presented was counterbalanced across subjects.

Results

Not surprisingly, the tracking performance was poor in the no warning condition, since subjects were required continually to look away from the task, to check on the LEDs. Performance in the other two conditions was better, with no significant difference between them, since in either case a subject could concentrate upon the tracking task, until a warning was given. The times to respond to the signals are shown graphically in Figure 6. Responses in the silent condition were predictably slower than in the warned conditions, but of more interest, responses following localized warnings were significantly ($p < 0.01$) faster than with central bleeps.

Discussion

At just over 300 ms, the time saving when responding to localized warnings was not great. Nevertheless, one third of a second is not a negligible interval, in the cockpit of a fast jet. An examination of individual responses revealed considerable inter-subject differences, and indeed, differences in response times to different locations, for a given subject. This effect must have been due, at least in part, to the nature of the localization cues. For the experimenter, the directional bleeps permitted large time savings, because he had considerable experience of the stimuli, but some subjects appeared to gain relatively little from the directional warnings, particularly for some directions. The experimental subjects were deliberately only given practice with the tracking task, since in everyday life we do not normally practice our sound localizing skills. The fact that some benefited less from the directional sounds may presumably be attributed to the lack of fidelity in the spectral cues, although there are doubtless also individual differences in the ability to localize natural sounds.

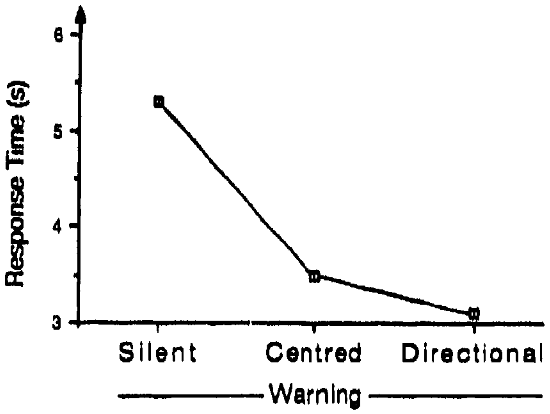

Figure 6 Mean signal response times in Experiment II

Taken together, the results of these two experiments are a strong indication that imposing synthetic direction cues upon sounds will facilitate the acquisition of spatial information. Moreover, even rather crudely represented localizing cues can begin to yield these improvements. It is to be expected that a refinement in the quality of cues will lead to a greater improvement in performance. However, this prediction needs to be tested, and research is now progressing, using a dummy head, with microphones in its rubber ears, to produce the required auditory stimuli.

The experiments reported in this paper have concentrated upon determining response times to discrete events, since this is a useful means of evaluating subject/stimulus interaction. However, if situational awareness is truly improved, then, although reaction times to specific stimuli will of course be reduced, this will not be due simply to the nature of those stimuli *per se*. The improvement will result from the general enhancement of situational appreciation. In these preliminary studies, such an overall effect could not be achieved, and its demonstration will have to await a larger scale simulation. It will come about as a result of imparting an artificial directional quality to all auditory signals. In this way the pilot would receive frequent reminders of his orientation, with respect to signal sources both within and outside his cockpit. Early results of tests with the dummy head offer some support for this statement. Subjects listened to a series of sounds, which had been recorded in stereo, via the dummy's ears. Localizing accuracy was assessed, by asking subjects to mark on a plan the position from which each sound seemed to come. These positions were later compared with the actual locations during recording. The test was repeated, in two conditions. In one, the sounds were produced just as described above, but during the other trial they were accompanied by a constant 'bleep', from a fixed location, marked on the plan. This background noise, although irrelevant to the task, provided a reference point - effectively improving situational awareness. The location judgements were significantly more accurate under this condition.

All the results reported in this paper are encouraging and, although ears will never be as important to a pilot as eyes, one looks forward to a time when the human can be just a little bit more like a bat!

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THE EFFECTS OF ACOUSTIC ORIENTATION CUES ON INSTRUMENT FLIGHT PERFORMANCE IN A FLIGHT SIMULATOR

by

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SUMMARY

An initial version of an Acoustic Orientation Instrument (AOI)--in which airspeed was displayed as sound frequency, vertical velocity as amplitude modulation rate, and bank angle as right-left lateralization-- was evaluated in a T-40 (Link GAT-3) motion-based simulator. Fifteen pilots and three non-pilots were taught to use the AOI and flew simulated flight profiles under conditions of neither visual nor auditory instrumentation (NO INPUT), AOI signals only (AOI), T-40 simulator instrumentation only (VISUAL), and T-40 simulator instrumentation with AOI signals (BOTH). Bank control under AOI conditions was significantly better than under the NO INPUT condition for all flying tasks. Bank control under VISUAL conditions was significantly better than under the AOI condition only during turning and when performing certain complex secondary tasks. The pilots' ability to use the AOI to control vertical velocity and airspeed was less apparent. However, during straight-and-level flight, turns, and descents the AOI provided the pilots with sufficient information to maintain controlled flight. Factors of potential importance in using sound to convey aircraft attitude and motion information are discussed.

INTRODUCTION

Spatial Disorientation (SD) is one of the major causes of military aircraft accidents; according to the U.S. Air Force Inspection and Safety Center it has caused or contributed to approximately 14% of all USAF class A accidents from 1980 through 1986. In 1988, for example, it was contributory in 12 class A Mishaps. SD is also a problem in civil aviation; it causes 16% of fatal general aviation accidents (1) and 12% of fatal airline accidents (2). Commonly SD occurs as a result of distraction or task saturation, when the pilot's visual system is occupied with processes other than spatial orientation, such as searching for other aircraft or examining something in the cockpit.

It is interesting to compare the percentage of operator-error mishaps caused by SD for different fighter/attack aircraft. The percentage is greater in certain newer aircraft, SD accounts for only 19% of F-4 accidents and 20% of F-15 accidents, but for 35% of F-16 accidents (3). In many respects our most modern aircraft give less warning of a change in attitude than older models because of the loss of auditory and other non-visual cues. An F-4 pilot recognizes changes in airspeed by the noise of the wind rush as speed increases. The responsiveness of the F-4 controls also changes with airspeed. In the F-16 the quiet cockpit gives much less warning of airspeed changes. The F-16 control input is via pressure sensors to the flight computer ("fly by wire"), giving the pilot minimal tactile or proprioceptive feedback. Malcolm contrasts the richness of the sensory experience of the Wright brothers flying exposed to the wind and elements to that of the modern F-16 pilot relying only on central vision to obtain attitude information from a 2-inch-diameter flight instrument (4). The reduction in variety of sensory inputs leaves the visual modality to carry most of the information load.

The space available for visual instrumentation is also restricted in contemporary fighter aircraft. The switch from the two-seat F-4 to the single-seat F-15 and F-16 halves the number of available cockpits for instrument placement, and seating the pilot high in the aircraft has further restricted the available instrument panel area of the contemporary fighter. For example, the F-4 attitude indicator is large (12.7 cm in diameter) and at just below design eye level. In the F-15 and F-16 these instruments are smaller (7.6 cm and 5.1 cm in diameter, respectively) and placed lower (35 degrees and 25 degrees below design eye level, respectively) than in the F-4 (5).

Thus two major problems in cockpit design which predispose to spatial disorientation are heavy visual workload and inadequate attitude displays. A potential solution for these problems involves the use of other sensory modalities. Investigators have shown that the pilot can handle more information by using other sensory modalities to supplement vision. There is a significant increase in processing capacity if both inputs and outputs are on different modalities; i.e., speech response to auditory input and manual response to visual input (6). An obvious example is the pilot flying an instrument approach and simultaneously talking to Air Traffic Control. Auditory signals are effective for warnings--the average reaction time to auditory signals is 1/6 second compared to 1/5 second for visual input (7).

By including directional information in acoustic signals delivered via pilot headsets, the number of possible uses of acoustic inputs in flight is increased (8). Acoustic signals using sound localization, for example, could display the direction of threats or other targets (9)(10). Spatial information delivered by auditory cues may be more compelling than visual input and produce less interference with other inputs (9)(8)(11).

The possibility of using acoustic signals to convey flight control/performance information was demonstrated in flight as early as 1936 (12). In 1945 Forbes demonstrated that auditory signals for at least three control/performance parameters (for example: turn rate, bank angle, and airspeed) were needed to maintain controlled straight-and-level flight in an aircraft simulator. After training for one hour pilots were able to attain performance levels comparable to those obtained with visual instruments (13). Neither of the above investigators provided information concerning the vertical motion of the aircraft (i.e., pitch, altitude, or vertical velocity). In 1948 Cornell Aeronautical Laboratory evaluated the feasibility of using acoustic signals to present glide path information (14). In 1952 Humphrey designed a system using acoustic signals to provide altitude information and course guidance (15).

Sound proved to be most useful, and was easy to learn, when it represented only one dimension of aircraft attitude (16). Ellis used pulse rate to present airspeed information to a pilot subject performing a visual tracking task in a flight simulator (17). This was the first study to quantify performance when acoustic signals were used and to analyze results statistically. Pilot performance was significantly better with the sound presentation alone than with the visual airspeed instrument alone. Hasbrook evaluated pilot performance with aural input, visual input, and both inputs combined to control of a single parameter (glide slope) (18). After only 20 minutes of practice, his pilots showed no significant differences in performance between the different display modes.

None of the above investigators evaluated a system capable of providing aircraft control through a variety of maneuvers such as turns, descents, etc. Neither did these investigators evaluate the effect of these acoustic signals on the ability of pilots to perform other cockpit tasks, although Forbes demonstrated that these auditory signals did not interfere with radio transmissions. Hasbrook specifically exempted the pilot from distracting tasks in order to test the acoustic device.

We were interested in the pairing of acoustic signal parameters with aircraft state parameters. DeFlorez, Forbes, Humphrey, and Cornell all used some variation of interaural intensity differences to convey information about turn or course deviations. Sound frequency (aural pitch) was variously used to indicate bank angle (13), altitude (15), or deviation from glideslope (14). Forbes suggested using signals that "sounded like the behavior of the airplane" such as a putt-putt sound for airspeed. Other investigators (e.g., Hasbrook), however, have been successful in using sounds arbitrarily assigned to a parameter; for example,the Morse code "A" ("dit dah") for above glide slope and the Morse code "N" ("dah dit") for below glide slope.

Acoustic signals have been used operationally only to present pilots with information on a single flight parameter. Early low frequency/medium frequency navigation signals represented course deviation with an acoustic signal: a Morse code "A" for one direction and a Morse code "N" for the other. These signals would fuse into a steady tone of 1,020 Hz when the aircraft was on course (19)(20). The F-4 currently incorporates an angle-of-attack (AOA) aural tone indication. Changes in both pitch and pulse rate indicate changes in AOA, thus helping pilots recognize dangerously high AOA's and also assisting them in maintaining constant AOA on final approach.

To free the pilot's visual system from the task of constantly monitoring aircraft attitude and motion, we provided the pilot with auditory spatial orientation information by means of a complementary flight instrument called an "acoustic orientation instrument" (AOI). The purpose of this investigation was to evaluate the ability of pilots to use sound signals to help control an aircraft in flight at times when their vision is occupied with tasks other than primary aircraft control. The premise is that the additional aurally presented aircraft control information will help pilots to fly with greater precision and safety, as they will be less likely to become spatially disoriented. This study was designed to examine, in a flight simulator, the ability of pilots to use an instrument that encodes aircraft flight parameters into an acoustic signal for controlling aircraft attitude and motion.

MATERIALS AND METHODS

Flight maneuvers were performed by the subjects in the USAF School of Aerospace Medicine (USAFSAM) T-40 (Link GAT-3) flight simulator equipped with an Acoustic Orientation Instrument (AOI). This simulator incorporates motion with up to 13 degrees of nose-up and 8 degrees of nose-down pitch rotation and 13 degrees of right and left roll rotation; it employs the usual washout, washback, and scaling common to sophisticated motion-based flight simulators. Ambient noise levels in this simulator were measured with third-octave bands. Levels peaked at 20 Hz (82 dB) and 120 Hz (78 dB). Above 120 Hz noise levels steadily decreased. From these measurements we determined that a reasonable operating range--200 Hz and above--was available for suprathreshold use of the acoustic device without overstimulation.

The AOI converted aircraft flight data into auditory information by shaping an acoustic signal delivered to the pilot through earphones. The AOI was controlled by the relatively slowly-varying analog signals from the simulator; these signals also controlled the readings on the traditional dial indicators for instrument flight. For this experiment the AOI mapped the changes in three flight parameters upon different dimensions of one acoustic signal.

Airspeed was represented as frequency (repetition rate) of a square wave which increased as airspeed increased. The square wave is operated upon to construct the other acoustic signals. The mean or center frequency of the acoustic signal representing airspeed was monotonically related to airspeed: e.g., an airspeed of 100 knots would create a 100-Hz acoustic signal, and an airspeed of 800 knots would create a 2,000-Hz signal.

Bank angle was indicated by interaural intensity differences--the signal amplitude in the ear on the same side as the direction of the bank was increased and the amplitude in the other ear was decreased. The simulator control signal for bank was used to control a digital attenuator in the AOI to reduce the acoustic signal to one ear. Interaural intensity differences were not sufficient to allow suitable discrimination of bank angles over the desired full range of +/-30 degrees of simulator bank. We therefore set limits in the AOI so that the interaural intensity difference reached its maximum at +/- 3 degrees. For simulated bank angles greater than 33 degrees a "wavering" sound was created by modulating the square wave amplitude to warn the pilot that the bank angle was extreme. Aural presentation of bank angle information required stereophonic earphones: we used conventional Koss K-6 "hi-fi" phones.

Vertical velocity was represented by modulating the amplitude envelope of the square wave. When altitude was neither lost nor gained there was no temporal modulation of the acoustic signal. When vertical velocity exceeded 100 ft/min amplitude modulation (AM) was imposed upon the signal. The rate of change of the signal amplitude was proportional to the vertical velocity. When the simulated aircraft descended the amplitude of the signal became greater in a crescendo fashion. When the sound intensity reached a predetermined maximum level, the intensity returned to a predetermined minimum and rose again, thus generating a sawtooth modulation of stimulus amplitude. A climb caused a decrescendo signal, with the rate of fall in signal amplitude proportional to the ascent rate of the aircraft.

Fifteen pilot volunteers, either military or civilian pilots with an instrument rating, were selected to participate in the study. Medical requirements included the possession of a USAF Flying Class II or an FAA Class III medical certificate and an affirmation by the pilots that they had no symptoms referable to balance and hearing. Three non-pilot subjects were also instructed in simulator flying and tested. All of the subjects were allowed to practice flying the simulator ad lib both with and without the AOI until they felt competent to fly the simulator under both conditions. Most of the subjects practiced a total of about two to three hours. The actual experiment consisted of a simulator flight lasting approximately one hour.

Variables recorded included airspeed, bank angle, vertical velocity, altitude, and heading. Airspeed, bank, and vertical velocity had acoustic analogs, while altitude and heading did not. The voltage signals representing each variable were sampled at 200 msec intervals, converted to appropriate units (e.g. ft/min for vertical velocity), and printed out. For statistical analyses, the mean squared error (MSE) and mean absolute error (MAE) of deviation from desired values for each of the flight parameters of interest were calculated for each critical 1- or 2-minute segment of the protocol.

Experiment 1. The purpose of this first series of experimental simulator flights was to evaluate the ability of pilots to use aural signals to perform a variety of flying tasks. Each subject flew a series of basic aircraft control manuvers which included straight and level flight, a level right turn at 30 degrees of bank, and a wings-level descent of 1,000 ft/min. Each of these maneuvers was flown for two minutes under each of three experimental conditions:

(1) Neither visual nor auditory instrumentation (NO INPUT)
(2) AOI signals only (AOI)
(3) T-40 simulator instrumentation only (VISUAL)

Experiment 2. The purpose of the second series was to evaluate the ability of pilots to use aural signals, alone and in combination with visual signals, to control the simulator in straight-and-level flight while distracted by secondary tasks. There were two separate two-minute protocols involving the addition of secondary tasks (distractions). Each protocol began with a one minute segment of straight and level flight. During the second minute of each protocol one of two tasks was introduced. The first task required responding first to a radio call to change a radio frequency and then to a request to change the transponder code (RADIO). Accomplishing this task in the T-40 involved bending over and to the right to the lower portion of the console between the left and right seats. The second task required looking up a radio frequency in a flight publication and changing to that frequency (LOOK-UP). A general ANOVA was performed testing the interaction of task performance with the various conditions. Generally, flying performance was significantly worse during secondary task performance. If in either task a frequency code was dialed incorrectly, the inside observer repeated the frequency or code to the subject until it was entered correctly.

Effectiveness of task performance was measured by the time it took to correctly complete the task as measured by the inside observer. Each of these protocols was flown for two minutes under each of four experimental conditions:

(1) Neither visual nor auditory instrumentation (NO INPUT)
(2) AOI signals only (AOI)
(3) T-40 simulator instrumentation only (VISUAL)
(4) T-40 simulator instrumentation and AOI signals (BOTH)

Each of the subjects were presented these various conditions (NO INPUT, AOI, VISUAL, and BOTH) in a different order, selected randomly, without replacement from the 24 possibilities to minimize possible order effects.

RESULTS

The Shapiro-Wilk Test for normality showed the mean absolute error (MAE) and the mean squared error (MSE) values for the 18 subjects' performance metrics to be essentially normally distributed. Examination of the distribution of individuals that the three non-pilot subjects' MAE and MSE performances were distributed differently from those of the pilots. This was confirmed by Box-Jenkins plots to detect outliers, which confirmed that these 3 subjects in many cases fell outside of the normal distribution formed by the other 15 subjects. Thus, for the statistical analysis presented below only data for the 15 pilot subjects were used.

The MAE and standard deviation (SD) for each combination of condition and flying task are shown in Table I for Experiment 1 and in Table II for Experiment 2. The SD's of both the MAE and the MSE varied markedly between the various conditions tested, making statistical inference testing with the MAE and MSE data somewhat difficult. The standard deviations of the performance data were highest for the NO INPUT condition, became progressively smaller for the AOI and the VISUAL condition, and were smallest for the BOTH condition. The SD of the MAE for bank control under the NO INPUT condition was in most cases more than 10 times that under the VISUAL condition, and the SD of the MSE for the NO INPUT condition was in most cases more than 100 times that under the VISUAL condition. These standard deviations were much more comparable after a logarithmic transformation of the performance data. Logarithmic transformations of the MAE's and the MSE's for each pilot subject were used for each of the specific task/condition combinations. Two-way analysis of variance procedures were used to compare the conditions for each experiment. Follow-up Duncan's multiple range tests were used to determine specific differences in the conditions for each task.

Experiment 1. Figure 1. shows the effectiveness of bank control for the initial series of flying tasks (with no secondary tasks added). Bank control was significantly better under the AOI condition than under NO INPUT for each flying task. Although performance was somewhat better for the VISUAL condition than for the AOI, the only statistically significant difference occurred for the level right turn (Table III).

Figures 2 and 3 show the results for vertical velocity and airspeed. Error was less in the AOI condition than in the NO INPUT condition for both these variables. The AOI condition was associated with significantly better control of vertical velocity and airspeed during descent and level right turn. For all three tasks, the error was least for the VISUAL condition; and control of vertical velocity and airspeed under the VISUAL condition was, in all cases, significantly better than under the AOI condition.

Experiment 2. Results in Experiment 2, for control of bank, vertical velocity, and airspeed were similar to those from Experiment 1. For Experiment 2 results for the BOTH condition are also shown, and performance after the addition of secondary tasks (distractions) is evaluated.

Figure 4 shows the results for bank control in the second experiment. As in Experiment 1, bank control was significantly better under the AOI condition than under NO INPUT for all flying tasks. Bank control under VISUAL conditions appeared somewhat better than under AOI, but the differences were not statistically significant except during the LOOK UP task. Bank control was better under the BOTH condition than under VISUAL except during performance of the LOOK-UP task, but these results did not achieve statistical significance (Table IV).

Figure 5 shows the relative effectiveness of vertical velocity control for Experiment 2. Control of this parameter was significantly better under the AOI condition than under NO INPUT for some of the flying tasks. For most tasks, however, vertical velocity control was also significantly better under the VISUAL condition than under AOI. Control under the BOTH condition was significantly better than under AOI in every case.

Figure 6 shows the relative effectiveness of airspeed control during this experiment. Airspeed control under the AOI condition was significantly better than under NO INPUT for the look up task. Moreover, control under the VISUAL condition was, in every case, significantly better than under the AOI condition, and BOTH was better than AOI in nearly every case.

Figure 7 shows the effects of the various conditions on secondary task performance as measured by time to task completion. The ANOVA showed significant differences

TABLE I. Performance of 15 pilot subjects during Experiment #1. The mean absolute error (MAE) and standard deviation are given for each combination of parameter and condition.

	NO INPUT	AOI	VISUAL
BANK (degrees)			
level flight	15.4+3.96	2.7+0.42	1.8+0.20
right turn	22.8+2.78	10.0+2.35	3.1+0.26
descent	22.1+3.16	4.6+1.38	1.9+0.18
VERTICAL VELOCITY (feet per minute)			
level flight	721+149	485+68	225+24
right turn	1670+118	1047+123	225+38
descent	1049+87	611+53	223+21
AIRSPEED (knots)			
level flight	13.9+2.14	10.9+2.60	4.6+0.92
right turn	32.2+3.75	22.1+5.37	4.7+1.37
descent	22.9+2.12	16.7+2.79	7.3+2.02

TABLE II. Performance of 15 pilot subjects during Experiment #2. The MAE and standard deviation are given for each combination of parameter and condition.

	NO INPUT	AOI	VISUAL	BOTH
BANK (degrees)				
level flight	12.5+3.26	3.0+0.63	1.8+0.21	1.4+0.14
LOOK-UP	26.6+4.58	6.1+1.12	2.8+0.40	2.8+0.34
level flight	14.8+3.79	2.5+0.42	1.6+0.22	1.4+0.13
RADIO	21.7+4.58	4.1+0.72	2.4+0.32	2.4+0.35
VERTICAL VELOCITY (feet per minute)				
level flight	789+127	485+101	222+24	205+24
LOOK-UP	1334+168	724+124	333+46	381+53
level flight	778+178	559+129	183+21	215+32
RADIO	1019+200	721+132	406+72	336+70
AIRSPEED (knots)				
level flight	9.9+1.88	8.6+2.23	3.4+0.68	4.8+1.20
LOOK-UP	24.0+3.58	15.3+3.90	4.2+0.67	4.8+0.65
level flight	10.1+1.98	10.1+2.03	3.4+0.48	3.5+0.59
RADIO	19.0+4.25	14.6+2.98	4.5+0.73	4.4+0.89

TABLE III. Logarithmically transformed MAE and MSE performance data of 15 pilot subjects for Experiment #1.

		NO INPUT	AOI	VISUAL
BANK				
level flight	MAE	2.2	.9*	.5*
	MSE	4.7	2.2*	1.4*
right turn	MAE	3.0	2.0*	1.1*+
	MSE	6.2	4.5*	2.4*+
descent	MAE	2.8	1.2*	.6*
	MSE	5.9	2.9*	1.7*
VERTICAL VELOCITY				
level flight	MAE	6.2	6.1	5.3*+
	MSE	12.7	12.5	11.1*+
right turn	MAE	7.4	6.8*	5.4*+
	MSE	14.9	14.0*	11.3*+
descent	MAE	6.9	6.4*	5.4*+
	MSE	14.0	13.0*	11.1*+
AIRSPEED				
level flight	MAE	2.5	2.0	1.3*+
	MSE	5.1	4.2	2.8*+
right turn	MAE	3.4	2.7*	1.3*+
	MSE	7.0	5.7*	2.7*+
descent	MAE	3.0	2.6	1.6*+
	MSE	6.4	5.3*	3.5*+

*Denotes significantly better than NO INPUT.
+ denotes significantly better than AOI.

TABLE IV. Logarithmically transformed MAE and MSE performance data of 15 pilot subjects for Experiment #2.

		NO INPUT	AOI	VISUAL	BOTH
BANK					
level flight	MAE	2.1	.9*	.4*	.3*+
	MSE	4.4	2.1*	1.4*	.9*+
LOOK-UP	MAE	3.0	1.5*	.9*+	.9*+
	MSE	6.2	3.4*	2.2*+	2.2*+
level flight	MAE	2.0	.7*	.4*	.3*
	MSE	4.2	1.8*	1.1*	1.0*
RADIO	MAE	2.7	1.1*	.8*	.7*
	MSE	5.6	2.6*	2.1*	1.9*
VERTICAL VELOCITY					
level flight	MAE	6.4	6.0*	5.3*+	5.2*+
	MSE	13.1	12.5	11.1*+	10.9*+
LOOK-UP	MAE	7.0	6.3*	5.7*+	5.8*+
	MSE	14.3	12.9*	11.8*+	11.9*+
level flight	MAE	6.1	6.0	5.1*+	5.2*+
	MSE	12.4	12.4	10.6*+	10.8*+
RADIO	MAE	6.6	6.3	5.8*	5.6*+
	MSE	13.4	12.9	12.1*	11.6*+
AIRSPEED					
level flight	MAE	2.0	1.9	1.0*+	1.3*
	MSE	4.3	3.9	2.2*+	2.7*+
LOOK-UP	MAE	3.0	2.4*	1.2*+	1.3*+
	MSE	6.2	5.0*	2.7*+	2.8*+
level flight	MAE	2.0	2.1	1.1*+	1.1*+
	MSE	4.2	4.3	2.4*+	2.3*+
RADIO	MAE	2.4	2.3	1.3*+	1.2*+
	MSE	5.1	4.8	2.9*+	2.5*+

*Denotes significantly better than NO INPUT.
+ denotes significantly better than AOI.
In no case do VISUAL and BOTH differ significantly.

between the four conditions for time to task completion for the LOOK-UP and the RADIO tasks. Task performance was fastest under the NO INPUT condition. This was an expected result since many subjects found that efforts to control the aircraft under the NO INPUT condition were largely futile; consequently they devoted all their effort to the secondary task. Interestingly, for the LOOK-UP task, performance time was the longest under the BOTH condition. The mean time to complete this task under the BOTH condition (42.6 seconds) was significantly longer than under the VISUAL and AOI condition (30.3 and 32.5 seconds)($p<.05$) and the NO INPUT condition (25.7 seconds)($p<.001$). The mean time to complete this task under the AOI condition was not significantly different from that under the VISUAL condition. For the RADIO task the time to complete the task was equal (27.4 seconds) for the VISUAL and BOTH conditions, and was significantly longer for those two conditions than for the NO INPUT condition (22.3 seconds)($p<.05$). The mean time to complete the RADIO task under the AOI condition (25.5 seconds) was not significantly different from any of the other conditions.

DISCUSSION

The acoustic input is clearly influencing the subjects' ability to control flight parameters. Bank proved to be the parameter most amenable to control by acoustic cues. Bank performance was better in level flight, however, than in a 30-degree banked turn. The bank MAE for the AOI condition was 18% of the level for NO INPUT in Level Flight, 21% of it in Descent, and 44% of it in Right Turn (Table 1).

The effectiveness of interaural intensity differences for conveying information about aircraft bank can be attributed to the salience of variations in the binaural signal and to the mapping of interaural intensity differences upon bank angle. The AOI used in this study was set so that a large change in interaural intensity difference would be generated between +3 and - 3 degrees of bank. With further increases in bank there was little further increase in interaural intensity difference, but at +/-33 degrees a warning sound was introduced. If the mapping of interaural intensity difference upon bank angle were made to be a different function, then the performance would also vary, according to the function. One should be able to produce a highly discriminable region by making the interaural intensity difference particularly detailed at a specified bank angle. Further exploration could define the values and costs of different functions mapping interaural intensity differences upon bank angle.

As noted above, interaural intensity differences alone were not sufficient to allow discrimination of a wide range of bank angles. One might expect a more salient signal to reduce further the MAE for auditory control. Several possible modifications to the AOI could result in improved discrimination of interaural differences and, therefore, bank angle.

(1) The AOI did not provide any interaural phase (time delay) to help in lateralization. Additional lateralization cueing could be obtained by adding interaural time delay.

(2) Appropriate filtering of the input to each ear to provide three-dimensional localization of sound, rather than mere lateralization, could improve the ability of subjects to discriminate bank angle.

(3) Both localization (lateralization) and identification are better with complex signals than with spectrally simple sounds. The increased salience of the image produced by broadband noise instead of the square wave used in this study should result in improved localization/lateralization.

(4) The variation in interaural intensity differences should follow a function relating the perceptual property (location) to stimulus dimension (interaural intensity). At present earphone input voltage is mapped as a linear function of bank angle. A small change in interaural intensity around zero intensity difference produces a large shift in lateral position of a sound image, with the amount of the shift depending on the intensity of the stimuli. As the image moves to a more lateral position, the function should become less steep, since greater interaural intensity differences are required to produce equal changes in image positions at more lateral locations.

(5) No provision for adjusting the interaural intensity differences as a function of frequency is included. If a constant bank angle is maintained as airspeed increases from low to high, the frequency of the square wave increases but the interaural intensity difference remains constant. Under these conditions the image moves toward the midline. A provision for adjusting the interaural intensity difference as a function of frequency should be added.

Vertical velocity proved difficult to control with the AOI only. The MAE in the AOI condition was 67% of that with NO INPUT for Level Flight, 63% for Right Turn, and 58% for Descent. We attribute this to two problems. First, control of vertical velocity without reference to pitch of the aircraft is somewhat difficult. Attempting to control the aircraft by using vertical velocity (a performance parameter) as opposed to using pitch (a control parameter) is contrary to what is taught in basic instrument flying training. Second, the signal chosen to represent vertical velocity was not easy to interpret. Subjects had some difficulty in distinguishing between the sound that indicated ascent and the one that indicated descent. The sounds were described as

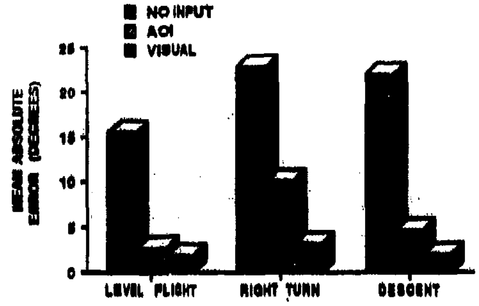

Figure 1. Deviation of bank from requested value

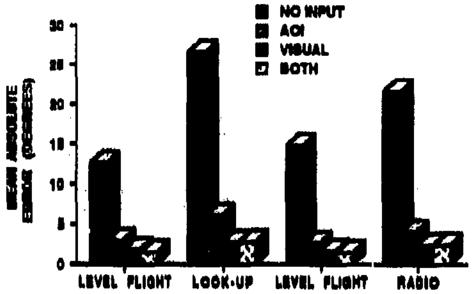

Figure 4. Deviation of bank from zero degrees

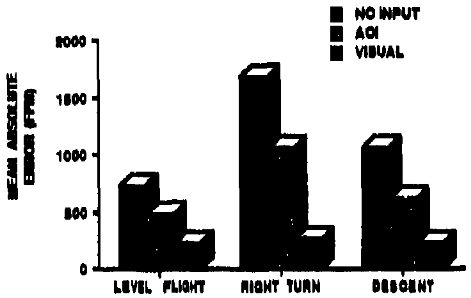

Figure 2. Deviation of vertical velocity from requested value

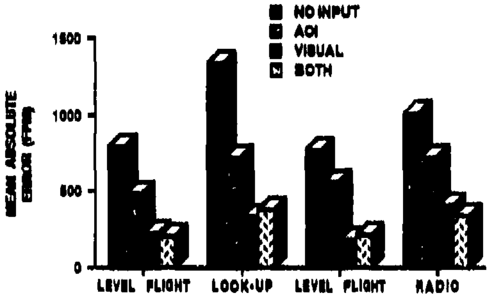

Figure 5. Deviation of vertical velocity from zero fpm

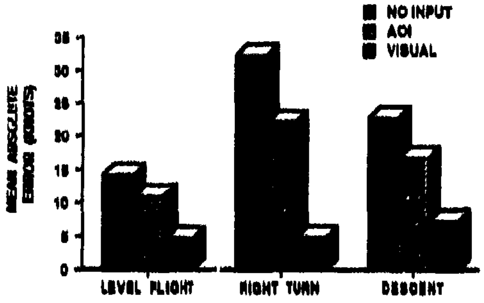

Figure 3. Deviation of airspeed from 300 knots

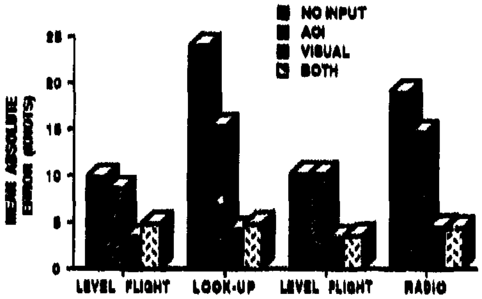

Figure 6. Deviation of airspeed from 300 knots

"confusing" and the difference between them as "subtle". One subject stated that modifying climb and descent required a "double cognitive effort. First you have to decide what the signal means." This situation is in contrast to that for bank control, where subjects learned easily (and remembered more readily) that increasing sound in one ear meant a banked turn in that direction.

Some of the limitations observed in controlling airspeed may be attributable to the characteristics of the base signal. There was no apparent difficulty in discriminating the auditory pitch change of the square wave when airspeed varied rapidly; however, there may have been some loss of pitch tracking, i.e., there was some evidence for an inability to maintain a steady auditory pitch for a prolonged period. The MAE for the AOI condition was 76% of that for the NO INPUT condition for Level Flight, 69% for Level Right Turn, and 73% for Descent. One might expect improved performance by incorporating a reference pitch to indicate target airspeed, and by providing a temporal frame or rhythmic structure for the presentation of the two signals, target and variable. Habituation, adaptation, or lack of salience of the square wave signal may allow it to drop out of awareness with the demands of another task. Although a square wave has a richer spectrum than a sine wave, a noise band presents a still richer spectrum and can have still greater salience.

Although the acoustic signals provided usable orientation information to the pilot, the addition of a secondary task still caused a degradation of flying performance (Table II and IV). Furthermore, the combination of the acoustic signal with the visual display may even degrade performance of a secondary task, as evidenced by the fact that the BOTH condition resulted in the slowest completion of the visual task (LOOK-UP, Figure 7). Several subjects specifically complained that the acoustic signal was bothersome when they were trying to accomplish the secondary tasks. Thus the decreased secondary task performance for the BOTH condition might be interpreted as resulting from an additional perceptual load. This finding is in concert with the known tendency of pilots to decrease cockpit noise levels during periods of high visual loading. By tailoring acoustic signals to meet criteria for "auditory comfort" as well as for discrimination such perceptual overloading might be avoided. Highly relevant in this regard is ongoing work in psychoacoustics on the capabilities of human subjects to discriminate among complex sounds and on the stimulus characteristics that permit such discriminations.

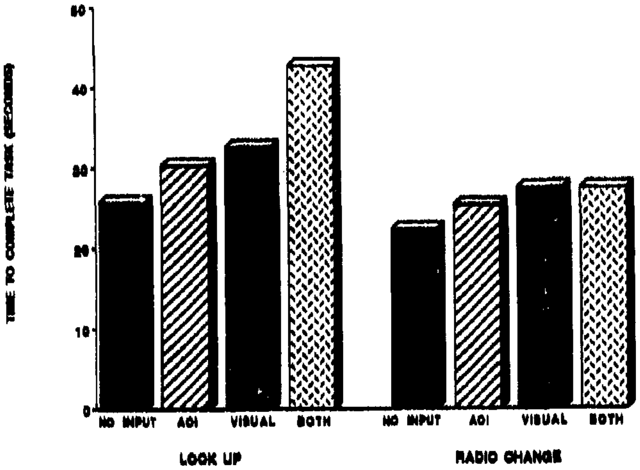

Figure 7. Mean time to complete task for each combination of condition and task

CONCLUSIONS

1. Acoustic signals can be useful indicators of the orientational state of an aircraft; interaural intensity differences, representing bank angle, are particularly effective in this regard. Using acoustic signals, a pilot can maintain level flight with no other input.

2. Under conditions of heavy workload when the pilot must complete certain secondary tasks requiring visual and cognitive activity, the presence of the additional auditory signal can compromise secondary task performance.

3. The results of the present study indicate that the potential benefit from use of of the Acoustic Orientation Instrument warrants continued exploration to define optimal signals for providing auditory orientation information to pilots.

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WORKLOAD INDUCED SPATIO-TEMPORAL DISTORTIONS AND SAFETY OF FLIGHT: AN INVESTIGATION OF COGNITIVE INTRUSIONS IN PERCEPTUAL PROCESSES

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SUMMARY

A theoretical analysis of the relationship between cognitive complexity and the perception of time and distance is presented and experimentally verified. Complex tasks produce high rates of mental representation which affect the subjective sense of duration and, through the subjective time scale, the percept of distance derived from dynamic visual cues (i.e., visual cues requiring rate integration). The analysis of the interrelationship of subjective time and subjective distance yields the prediction that, as a function of cognitive complexity, distance estimates derived from dynamic visual cues will be longer than the actual distance whereas estimates based on perceived temporal duration will be shorter than the actual distance.

This prediction was confirmed in an experiment in which subjects (both pilots and non-pilots) estimated distances using either temporal cues or dynamic visual cues. The distance estimation task was also combined with secondary loading tasks in order to vary the overall task complexity. The results indicated that distance estimates based on temporal cues were underestimated while estimates based on visual cues were overestimated. This spatio-temporal distortion effect increased with increases in overall task complexity.

This finding has important implications for the aviation community. In high speed, low level flight the aviator's situational awareness is dependent upon veridical spatial and temporal perception. If the complexity associated with flying high performance aircraft can induce spatio-temporal perceptual distortions, then safety of flight could be severely compromised. These perceptual distortions could lead to a situation where an aircraft approaches closer than intended to a target because the perceived visual distance was greater than the actual distance. In the extreme, this could lead to "pilot fascination" incident where an alert pilot flies an airworthy aircraft into the target. In addition, responses based on temporal cues (e.g., weapons release) could occur sooner than intended which would also compromise mission safety and effectiveness. This finding suggests that factors which reduce the cognitive load on the pilot (e.g., the incorporation of decision support systems in the cockpit), should lead to more accurate spatio-temporal perception which would also enhance the pilot's overall situational awareness.

1. INTRODUCTION

High speed low level flight is rapidly becoming a tactical necessity for many aircraft types. In these flight regimes fractions of a second mean the difference between an on target weapon and ground impact. It has long been understood that motor and cognition related delays in reaction time can play an adverse role in aircraft manual control and it has more recently been widely argued that increasing aircrew workload and task complexity can cause a loss of situational awareness (LOSA) which, in turn, leads to poor aircraft control decisions. It is, however, the case that only a limited understanding of underlying cognitive processes exists to describe, explain and predict cognitive influences on perceptual and motor functioning relevant to aviation. Perceptual influences on cognition, such as the illusions attributed to abnormal stimulation of the vestibular system, are rather better documented. Nevertheless, these observations underscore the importance of properties of human cognitive functioning in issues of engineering importance to aviation.

In this paper a new perceptual-cognitive effect related to a pilots spatial orientation capabilities is theoretically predicted from first principles and experimentally verified. High rates of mental representation associated with task complexity are predicted to affect the subjective sense of duration and, through the subjective time scale, affect the percept of a constant distance derived from dynamic cues. As a function of cognitive complexity, the perceived visual distance is predicted to be greater than the actual distance, leading to the possibility that the aircraft will approach much closer to a reference point than the intended separation distance. Under the same cognitive task demands another prediction derives that is, at first consideration, paradoxical. The prediction states that perceived time intervals will be longer than objective time intervals. Therefore, based on duration estimates, one would tend to act too soon rather than too late (as a function of cognitive complexity) as is the case with visual estimates. Both of these theoretical results are found to hold in the experiment.

The distance judgment distortion effect corresponds in form to the "pilot fascination" phenomenon that has long been a part of high performance aircraft operations. In a pilot fascination incident an alert pilot flies an airworthy aircraft into the target. The time interval judgment distortion effect has also been widely reported in the aviation literature and folklore in a variety of circumstances that correspond to situations and conditions that would be associated with high mental representation rates such as ejection and air to air weapons release (Carson, 1982, 1983).

Pilot fascination and distortions in temporal perception are often attributed to a generalized LOSA on the part of the aviator. The present study focuses on perceptual distortions induced by cognitive processing load which affect a pilot's sense spatial orientation. Although spatial disorientation (SD) is often attributable to dysfunctions in the vestibular system (e.g., Clark & Graybiel, 1956; Gillingham & Kurtz, 1974) or to degraded visual input (e.g., Bensen, 1978; Kirkham et al., 1978; Tredici, 1980) there are many cases in which the vestibular and visual inputs are normal and the "pilot simply flies the plane into the ground" (McNaughton, 1981; also see Haber, 1987; Tyler & Furr, 1971). The fact that a large percentage of SD incidents can not be accounted for in terms degraded perceptual input leaves open the possibility that other cognitive factors may be involved.

One factor that might influence a pilots spatial and temporal perception is the cognitive processing demands associated with flying high performance aircraft. There is a large body of evidence indicating that the perception of temporal durations is influenced by cognitive factors e.g., Fraisse, 1963; 1983; Michon, 1965; 1966; Ornstein, 1969). In general, estimates of the temporal duration of an interval increase concomitantly with the complexity of the stimuli that were processed during the interval. This finding is in agreement with the position that the percept of duration is based on the succession of mental events or representations. That is, the experience of time appears to be functionally related to the number and complexity of the representations that are generated to encode experiential events (c. f. Barrett, 1985; Block & Reed,. 1978; Fraisse, 1963; 1983; Ornstein, 1989). There is also evidence indicating that the perception of temporal durations influences judgments of apparent distance (Abe, 1935; Cohen, Hansel & Sylvester, 1953; Haung & Jones, 1982; Helson, 1930; Helson & King, 1931; Masshour, 1964). Although it is clear that cognition influences the percept of both space and time, the exact nature of this relationship is unclear (c.f., Jones & Haung, 1982; Masshour, 1964; Ono, 1976).

2. FORMALIZING THE SUBJECTIVE TIME SCALE

In this section the idea of cognition as a representing process and its relationship to perceived duration are described. The process of representing is taken to be one of creating structures of conceptual atoms and relations among the atoms such that the expectation of behavior entailed by the structure corresponds in some sense to observation. This amounts to a theory (trans)formation and confirmation process and is related to the problem of nondemonstrative inference (Carnap & Jeffery, 1971; Holland, et al., 1987; Kuhn, 1962; Randall, 1970). When cognition is approached in this fashion, a rough statement of what is done by a cognitive system is that it produces sequences of representation states. A sequence of representation states can be thought of as a code for a hypothetical world state, including actions of self and others. The complexity of a code is a function of its length. Energy is required in order for a system to enter into a representation state and is the measure of work performed by the representing system. A representational event is the occurrence of a representational state at a clocktime coordinate. The rate at which events are produced constitutes a power requirement on the system. A power requirement is the workload experienced by the system. Thus, under the confirmation-related time constraints imposed by the world event under observation, a more complex representation can be expected to impose a higher work load by requiring a higher representational event rate.

The following list of definitions serve as the premise for the subjective time scaling function that is described below. These definitions can be formalized, but for the purposes of the following development, this is entirely adequate.

A "code element" is a symbol required for each relation explicitly preserved by a code

A "code" is an arrangement of code elements, together with the rules of arrangement and interpretation.

A "descriptive structure" is any relation preserving form.

The "complexity" of a descriptive structure is a function of the number of relations that it explicitly preserves. Notice that many relations may be implicitly preserved

To "represent" is to encode in a descriptive structure.

A "representational event" is defined as a code element occurrence at a clock-time coordinate.

A self-clocked event driven, representational system is one that has internal access to estimates of extension in time only as sequences of representational events. That is, such a system has no homunculus with access to an objective clock. An event occurrence is the subjective temporal unit. One can imagine such a system giving estimates of objective time intervals that vary as the complexity of the descriptive structure which exists during the time interval being estimated varied. This would be the case because the number of representational events, (i.e., the subjective duration) entered into during the time interval would vary with the complexity.

To formally characterize the subjective time scale, the cumulative event function is introduced, (see Fig. 1; Barrett, 1985). The function is portrayed as continuous because there can be no subjective awareness of the absence of representation and no associated experience of duration. It is portrayed as non-decreasing because an event occurrence cannot unoccur. In the figure, it can be seen that the time interval (a,b) is not subjectively equal to the corresponding equal time interval (b,c) because the number of events in the time intervals are not the same.

Formally, the cumulative event function is given by,

$$\pi(t) = \int_0^t \frac{da}{\lambda(a)} \,. \qquad (1)$$

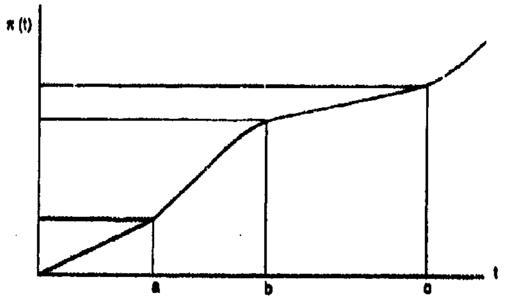

Fig. 1. The cumulative event function, π (t).

λ(α) is a time scaling function with units, unit-time per representation event. Notice that the instantaneous event rate, which is proportional to the workload on the system, is the time derivative of π(t).

$$\frac{\partial}{\partial t}(\pi(t)) = \frac{1}{\lambda(t)} \quad . \tag{2}$$

λ(t) is just the time scaling function that gives π unit slope, as in Fig. 2. Thus, λ(t) is the subjective time scaling function for the event driven system.

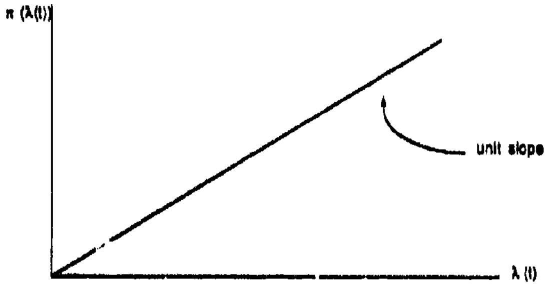

Fig. 2. Time-scaled cummulative event function.

The prediction concerning time intervals of equal subjective duration is written,

$$\|(a,b]\| = \|(b,c]\| \text{ iff } \pi_a^b = \pi_a^b \quad . \tag{3}$$

That is, the percepts of the intervals (a,b] and (b,c] are equal when the measures of the number of representational events occurring in intervals are equal.

Therefore, when λ^{-1} is large, (that is, when the representational work-load on the system is large), time intervals will seem longer than when the objective time intervals will be overestimated and actions sequenced in the subjective time scale will occur objectively sooner than in a low representational event rate situation.

3. A PREDICTION CONCERNING THE PERCEPT OF DISTANCE FROM DYNAMIC CUES

This section will develop some simple consequences of extending the elementary relationship relating rate, time and distance to the case of subjective distance derived from the rate of change in the subjective semi-static position in the subjective time scale, that is,

$$D_s = r_s \lambda \ . \tag{4}$$

The situation to be referenced is depicted in Fig. 3. The two trajectories have time location marks indicated in order to show their relative positions and separation distances at those marks. The actual separation distance is denoted D_a and the closure rate as r_a.

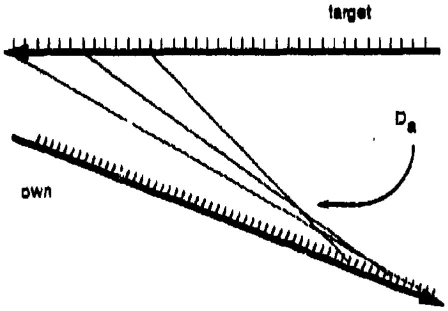

Fig. 3. Trajectories and closure distances.

In Fig. 4, D_a is plotted against time in the situation function, S. The time derivative of this function is the actual closure rate.

Fig. 4. The situation function, S.

A thought experiment is proposed where a "snapshot" is taken at each time mark and a "semi-static" distance estimate is made. These estimates are called semi-static because we acknowledge that there are dynamic cues available in the snapshot views. Some of these cues are explicitly available (e.g., blur). Others are characterized by changes that exist from view to view, such as changes in relative size, appearance of visual details, etc. Since such a list seems endless and because the restriction to a no-memory case from view to view seems too restrictive, we allow all such aspects of the decision estimate to be made from the stroboscopic views. All of this information is imagined to be carried in the function S. Each of the semi-static distance estimates is plotted in Fig. 5, forming the semi-static psychophysical function of the actual situation, F(S).

From the figures, the following relations and definitions are of interest.

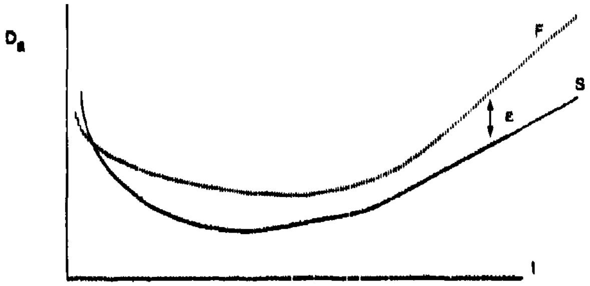

Fig. 5. The semi-static psychophysical function, F.

ε is the normed semi-static psychophysical error,

$$\varepsilon = (F - S)/S \quad . \tag{5}$$

δ is the direction of F taking S as a parameter,

$$\delta = \frac{d}{dS}(\varepsilon) = \frac{d}{dS}\left(\frac{F}{S}\right) \quad . \tag{6}$$

γ is the compliance of F taking S as a parameter,

$$\begin{aligned} \gamma &= \frac{d}{dS}(F) \\ &= S\delta + (\varepsilon + 1) \\ &= S\varepsilon' + \varepsilon + 1 \quad . \end{aligned} \tag{7}$$

$$r_s = \frac{\partial}{\partial\lambda}(F) = \frac{d}{dS}(F) \cdot \frac{d}{dt}(S) \cdot \left(\frac{d}{dt}(\lambda)\right)^{-1} = \gamma\, r_s \frac{d}{d\lambda}(t) \quad . \tag{8}$$

Substituting Eq. (8) into Eq. (4) and rearranging obtains the expression of the relationship of the subjective distance estimate derived from dynamic information.

$$D_s \frac{d\lambda}{\lambda} = \gamma\, r_s \, dt \quad . \tag{9}$$

In the situation where one is concerned with the actual distance associated with a subjectively constant distance, integration of both sides and manipulation yields,

$$\lambda(t)^{-1} = k_0 \, k_1{}^{1-\gamma} \exp\left(-\gamma \frac{D_a}{D_s}\right) \quad . \tag{10}$$

From this expression, it is apparent that as the representation rate gets big, D_a gets larger than D_s . It is this distance percept distortion prediction and the distortion of the percept of duration from Eq. (3) that are tested in the experiment described in the section.

4.0. EXPERIMENT

4.1 Introduction

An experimental paradigm was developed to test the theoretical predictions derived above. In this paradigm subjects were required to estimate distances under conditions where the available cues were either primarily visual or temporal in nature. The distance estimation task required subjects to judge when a pip moving down a CRT screen reached a predetermined destination point. In the visual cue condition, the pip appeared partway through its flight path down the screen and then remained visible until it went off the bottom of the screen. In the temporal cue condition, the pip started at the top of the screen which allowed subject to estimate the pip's velocity but then disappeared partway to the destination. Therefore, in the visual cue condition, distance estimates could be based on visual information because the pip was visible during the period when the response had to be made (i.e., as the pip approached and passed the destination point). On the other hand, in the temporal cue condition, there was no visual information present during this response period which insured that the judgment would be based on timing cues. The distance estimation task (in both the visual and temporal cue conditions) was performed under four different degrees of task loading in order to create varying degrees of overall task loading in order to create varying degrees of overall task complexity. This resulted in the following four conditions: (1) distance estimation only (baseline), (2) distance estimation and a cognitive threat assessment task (cognitive), (3) distance estimation and a pursuit tracking task (tracking), and (4) distance estimation combined with both the cognitive and tracking tasks (overall). Thus, the paradigm allowed for the assessment of the accuracy of spatio-temporal perception while the cognitive and/or motor complexity of the tasks varied.

Based on the preceding theoretical development, it was predicted that distance estimates in the temporal cue condition would be shorter than the actual distance whereas estimates in the visual cue condition would be longer than the actual distance. Furthermore, this spatio-temporal distortion effect should increase concomitantly with increases in overall task complexity. The experiment evaluated both pilot and non-pilot populations. It is possible that pilots, who have a tremendous degree of experience with tasks in which the estimation of time and distance is critical, would be more accurate in their perception of time and distance under conditions of high cognitive loading.

4.2. Method

4.2.1. Subjects. Two groups of eight subjects each were used in this experiment. The first group consisted of eight naval pilots currently stationed at the Naval Air Development Center (NADC). All of the pilots were currently qualified, although on different platforms (i.e., P-3, helicopter or jet). The second group consisted of eight, non-pilot, male employees at NADC. All subjects participated individually in a single experimental session lasting approximately one hour.

4.2.2. Apparatus and Stimuli. The presentation of stimuli, control of timing intervals and recording of data were all carried out on an AMIGA 2000 microcomputer with a Commodore 1084 color monitor.

4.2.3. Procedure. All of the tasks were presented within a whole-screen window on the color monitor. The window was black with white borders and measured 26 cm wide by 17.5 cm high.

Each task was first practiced in isolation. During the practice session subjects received 5 minutes of practice with the tracking task, 20 trails on the cognitive threat assessment task and 30 trials on the distance estimation task (15 visual cue and 15 temporal cue). There were a total of 180 experimental trials. These consisted of 30 baseline trials (15 in each cue condition) and 50 trials (25 in each cue condition) in each of the three loading conditions (cognitive, tracking and overall). Each of the three tasks will now be explained in more detail.

4.2.4.1. Distance Estimation Task. The distance estimation task required subjects to estimate when a pip (a white circle measuring 0.5 cm in diameter) moving down the center of the window reached a destination point that was located 14 cm from the top of the window (approximately three-fourths of the way down the screen). A line representing the destination point and the location of the pip when it was stopped were shown to subjects after each response during the practice session to facilitate learning the appropriate distance. During the test session only the location at which the pip was stopped was indicated. Both the velocity of the pip and the point at which it appeared (in the visual cue condition) or disappeared (in the temporal cue condition) were varied randomly which insured that the distance estimates could not be based on a strategy such as counting. In the temporal cue condition the total flight time of the pip (i.e., the time the pip required to travel from the top of the window to the destination point) ranged between 4 and 10 seconds. This flight time was broken into two sections dependent upon whether the pip was in a blanked (invisible) or unblanked (visible) state. The pip started out at the top of the screen in a visible state and travelled downward for between 2 and 5 seconds. At a randomly determined point located in the center one-third of the window the pip was blanked and then continued to move down the screen for another 2 to 5 second period before reaching the destination point. If the pip was not stopped by a response it continued downward for 12 cm beyond the destination point (well beyond the bottom of the screen). The visual cue condition was similar except that the pip started in a visible state at a randomly determined point in the center third of the screen (corresponding to the point where the pip was blanked in the temporal cue condition) and then continued to travel downward for between 2 and 5 seconds before reaching the destination point. Again, the pip would continue for an additional 12 cm, or until stopped by a response. The velocity of the pip was varied randomly between trials (subject to the above time constraints) in both the visual and temporal cue conditions.

4.2.4.2. Tracking Task. The tracking task was a one-dimensional pursuit tracking task in which subjects attempted to keep a line cursor within a rectangular box that served as the target.

4.2.4.3. Cognitive Threat Assessment Task. This task required subjects to decide whether an array of between four and eight symbols represented a threat or non-threat situation. The symbol set was comprised of four unique characters (@, &, +, ^). Two of the symbols were designated as friendly (+, ^) and two were designated as hostile (@, &). One of the symbols in each set was assigned a value of 1 and the other symbol was assigned a value of 2. If the sum of the hostile symbols in the array was greater than the sum of the friendly symbols then the array represented a threat otherwise it was a non-threat. The amount of time that the array was visible was controlled so that in both the visual and temporal cue conditions the threat array was presented during the final 2 to 5 seconds of the pip's flight. No feedback was presented for correct responses, but incorrect responses were followed by a short auditory tone indicating an error.

4.3. Results. The data in both the temporal and visual distance estimation conditions were assessed in terms of difference scores that were computed for each response by subtracting the pip flight time (i.e., the amount of time from the start of the pips flight until the subject's response) from the time the pip actually required to reach the destination. This procedure yielded a time score (in seconds) where a perfect estimate of the distance received a score of 0, underestimates resulted in a negative score and overestimates resulted in a positive score.

An initial four-factor analysis of variance (Order X Cue Type X Task Condition X Subject Type) was conducted to insure that presentation order did not influence the data. This analysis indicated that the order effect was nonsignificant, $F < 1$, and order did not interact significantly with the other variables (all $Fs < 1.7$ $ps > .1$). This allowed us to collapse across order for all further analyses. The means of subject's mean difference scores are presented in Table I as a function of cue type, condition and subject type. The effect of subject type was also nonsignificant $F(1,14) < 1$, and subject type did not interact with the other variables, (all $Fs < 1.4$, $p > .29$) which indicated that pilots and non-pilots did not differ in their estimates of distance in either the visual or temporal cue conditions.

The effect of cue type was highly significant $F(1,14) = 32.8$, $p < .0001$. This reflects the fact that distance estimates in the temporal cue condition were always shorter than the actual distance whereas estimates in the visual cue condition were always longer than actual distance (see Fig. 6). There was also a significant cue type by task type interaction, $F(1,14) = 6.7$, $p < 01$. An analysis of the effect of cue type within each level of task loading indicated that cue type was highly significant in each of the four loading conditions (all $Fs(1,15) > 24.0$, $p < .001$). However, the main effect of task load was only significant in the case of temporal cues, $F(1,15) = 4.7$, $p < .05$.

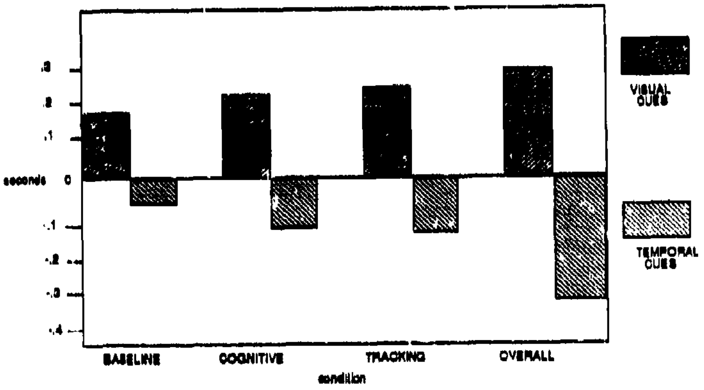

Fig. 6. Mean Difference scores as a function of condition.
(collapsed across subject type).

In order to assess the effect of task loading the baseline condition was compared to each of the other task loading conditions for both temporal and visual judgments. In the case of temporally based judgments, the baseline condition did not differ significantly from either the cognitive condition, $F(1,15) = 1.4$, $p > .25$, or the tracking condition, $F(1,15) = 2.7$, $p > .1$. Judgment times in the baseline were significantly shorter than those in the overall condition, $F(1,15) = 15.4$, $p < .01$. The same pattern was present for visual cue judgments in that the baseline did not differ significantly from either the cognitive condition, $F(1,15) = 2.4$, $p > .1$, or the tracking condition, $F(1,15) < 1$. However the judgment times in the overall condition were significantly longer than those in the baseline condition, $F(1,15) = 8.3$, $p < .05$.

Analyses were also conducted on performance in the loading tasks. In the tracking task the dependent measure was the average absolute error (in pixels) between the cursor and the center of the target box. The effect of subject type was nonsignificant $F(1,14) < 1$, and subject type did not interact significantly with the other variables, all $Fs < 1.5$ $p > .2$, indicating that pilots and non-pilots did not differ. There was a highly significant effect of task load, $F(1,14) = 38.7$, $p < .0001$, indicating that tracking performance was worse in the overall condition (mean error = 132.7) than in the tracking condition (mean error = 80.9).

Performance on the cognitive task was assessed in terms of the percent correct. Once again, the effect of subject type was nonsignificant, $F(1,14) = 1.9$, $p > .1$ and subject type did not interact with other variables, all $Fs < 1$. The only significant effect was that of task load, $F(1,14) = 5.6$, $p < .05$, reflecting the fact that performance was worse in the overall condition than in the cognitive condition (80 and 85 percent correct respectively).

4.4. Discussion. The present experiment evaluated whether cognitive processes influenced the perception of time and distance. Specifically, the study assessed whether perceived distances based on dynamic visual cues (those requiring rate integration) differed from percepts based on temporal cues and is so whether this difference increased with increases in the cognitive complexity of the task. The results indicated that dynamically based visual cues and temporally based cues produced opposite effect on perceived distance. That is, estimates based on dynamic visual cues were always longer than the actual distance whereas estimates based on temporal cues were always shorter than the actual distance. This finding provided strong support for the prediction that subjects would respond too soon when their estimates were based on timing cues and too late when their estimates were based on dynamic visual cues. The spatio-temporal distortion effect (i.e., the difference between visually based and temporally based distance estimates) was significant in each of the task loading conditions, including the baseline condition. Cognitive processing load was also shown to have an effect in that the spatio-temporal distortion was larger in the overall condition than in the baseline condition. However, the fact that a substantial spatio-temporal distortion effect was present in the baseline condition resulted in the baseline condition not differing from either the cognitive or the tracking condition.

The results also indicated that pilots and non-pilots did not differ in terms of the accuracy of their spatial and temporal judgments. It was expected that the pilot's previous experience with temporal/spatial judgments would reduce the overall complexity of the task and thereby attenuate the spatio-temporal distortion effect. However, the nature of the spatial and temporal judgments in the present experimental setting differs greatly from those normally experienced by pilots. For example, distance judgments are generally made in a three dimensional environment (i.e., judging the relative distance from a given object) rather than the two dimensional setting used in the present experiment. It seems likely that if the distance judgments were made in a more realistic environment (e.g., a flight simulator) that a difference between the two populations would emerge. Such a study would also allow for a better assessment of the relationship between the spatio-temporal distortion effect and LOSA.

5. CONCLUSION

From first principles it is possible to theoretically predict the effect of complexity of representation on the percept of time intervals and distance intervals derived from subjective rate integration. The present study has demonstrated that cognitive processes impact the perception of both time and distance and these effects should also influence an aviator's sense of situational awareness. For example, a typical ground attack profile requires that a series of precise motor sequences be executed as the pilot approaches the target while using out-of-the-cockpit visual cues. As the cognitive workload increases on target approach, two effects would be expected. First, motor responses based on timing cues should be executed too soon (e.g., a premature weapon release) as the aviator will subjectively feel that more time has elapsed than is actually the case. Second, the distortion in perceived distance will lead the aviator to approach closer to the target than intended which jeopardizes mission safety and in the extreme could result in a ground impact. Furthermore, it is unlikely that the aviator would be aware that his percept was inaccurate (i.e., a Type I LOSA; Bensen, 1978) and therefore it is unlikely that the effects could be compensated for.

The fact that spatio-temporal perceptual distortions are induced by the complexity associated with piloting modern, high-performance aircraft suggests that factors which reduce cognitive processing demands should also lead to a more veridical perception (Barrett, 1988). This provides a general rationale for the incorporation of dynamic decision support systems (D^2S^2) in advanced cockpits. The reduction in the cognitive load on the pilot engendered by such systems would be expected to enhance the aircrew's situational awareness and concomitantly increase both mission effectiveness and aircrew safety.

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EXPERIMENTAL TESTS ON THE MINIMAL VISUAL ACUITY REQUIRED FOR SAFE AIR CREW AND AIR CONTROL PERSONNEL PERFORMANCE

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Summary:

National and international directives specify minimal requirements for corrected and uncorrected visual acuity in military as well as civil aviation. There is a striking difference between the corrected visual acuity and the minimal visual acuity specified as a lower limit. Does this minimal acuity actually have any functional importance? The present experimental study concerning military pilots deals intensively with the minimal requirements on visual acuity which guarantee the safe operation of an aircraft. The investigation revealed that the specified visual acuity without correction as stated in all directives is not acceptable as a lower border limit for safe operation of an aircraft. It would therefore be possible to dispense completely with specified minimal uncorrected visual acuity values. However, a safe wearing of visual aids at all times, considering cockpit environment specific conditions must then be guaranteed. For air control personnel the uncorrected visual acuity should not have further significances. In additional studies we examined the minimal requirements for the radar controller. While reducing the visual acuity in defined steps the radar controller had to recognize critical situations during a simulated approach. For the special situation of the tower controller a visual acuity of 1,0 is required. Our tests with radar controllers reveal that a reduced visual acuity between 0,5 and 1,0 had no significant influence on the failure rates. The visual acuity in that range is not as important as for pilots and tower personnel.

Specific minimal visual requirements with and without glasses are indispensable for safe operation of an aircraft. LORENZ, 1943 (1) already pointed out the close connection between flight performance and visual acuity. Not only the ICAO but also the different national standards include specific minimal visual acuity values. It is most surprising that no experimental scientific study on actually needed minimal visual acuity has been performed until now. For this reason a study was conducted in cooperation between the Hamburg University Eye Department, the German Air Force and Lufthansa. In a jet aircraft simulator of the German Air Force we examined the minimal visual acuity needed for different flight conditions and operational functions during instrument flight and visual flight, where the pilot obtains most optical informations by looking out of the window. The transition from analog to digital displays or hand-up-displays requires to identify different types of optical informations very quickly. Additional demands for the pilots eye are changing distances, directions, brightness levels and colours of important flight informations. There is no doubt that such complex visual requirements need specific visual limits. At present there are different national and international directives as shown in the following index:

<u>Aviation Regulations</u>: VISUAL ACUITY	
German Civil Aviation Regulations (1988)	German Bundeswehr (1980)
I/II: c.c. 1,0/0,5 or 0,7/0,7 (± 3 dpt) former: s.c. 0,3/0,3 III: c.c. 0,5/0,5 (± 5 dpt) former: s.c. 0,1/0,1	I: s.c. 0,5/0,5 c.c. 1,0/1,0 II: s.c. 0,3/0,3 c.c. 1,0/1,0 III: s.c. no standard c.c. 1,0/1,0
U.S. Civil Aviation Regulations (FAA)	U.S. Airforce (1983)
I/II: s.c. 0,2/0,2 c.c. 0,7/0,7 III: s.c. no standard c.c. 0,6/0,6	I: s.c. 1,0/1,0 IA 21 years: s.c. 0,1/0,1 c.c. 1,0/1,0 II: s.c. 0,1/0,1 c.c. 1,0/1,0 III: s.c. 0,05/0,05 c.c. 1,0/0,7

Besides these standards Commercial Air Lines have much stricter qualification values. Particularly in Europe the entrance tests for civil pilots require an uncorrected visual acuity of 1,0 on both eyes (2,3). If one looks at the standards for minimal visual acuity one should ask which objective criteria have been used to establish these requirements. For example commercial aircraft pilots wearing glasses should have a visual acuity of 1,0 in both eyes but an uncorrected acuity of only 0,3 has been considered to be sufficient too. Even worse: Parachutists (Cat. III) for instance have to select very quickly a safe landing point (4) under similar visual requirements (s.c. 0,1). Also glider pilots (Cat. III) have to organize every phase on their flight without using an instrument from take off, estimation of flight path and looking for a suitable landing point under the same category for the uncorrected visual acuity. The accepted large difference between the limits for the corrected and uncorrected visual acuity levels can only be explained by the assumption that a pilot does not only carry along a spare pair of glasses in any case but he also is able to put it on immediately after loss of his glasses in case of an emergency. The importance of the uncorrected visual acuity level will appear in a quite different light if you consider the glider pilot in turbulent air or even the parachutist whose glasses are swept from his nose. Is the limit for the uncorrected minimal visual acuity really the limit of a certain visual level to terminate a flight or is it simply an alibi value of no functional importance? If we assume that this value should be of some, however little functional importance, it is worthwhile to look at it in more detail.

First we performed experimental tests which should quantify the relation between visual acuity and flight performance. 18 military pilots whose visual acuity was reduced in defined steps by so called "Bangerter foils" hat to accomplish special tasks during a simulator program. Another test was performed by commercial pilots in a similar way. We noted specific observation, all operational errors, the required time and finally an overall evaluation of the respective simulator mission. The military pilots were examined in a Tornado simulator with digital and analog indicators. Similarly, routine actions had to be accomplished. Sudden emergencies as engine failure, temperature problems, pressure decrease in the hydraulic system etc. were integrated in the simulator program to be able to check the time needed for recognition, allocation and inition of counter measures under aggravated vision conditions. In addition to monitoring the external areas through the windows the instruments had also to be monitored at distances between 76 and 40 cm.

A very high visual acuity level of about 0,9 was needed for the correct reading of the moving map display indicator. A visual acuity level of even 0,8 is needed for adjusting specific instruments which are important for approach. For rather essential functions a minimal visual acuity of 0,6 mostly was sufficient. The pilots stated that in case of an emergency they still regard a visual acuity level of 0,6 as sufficient for terminating a flight safely. The weapon system operator who is fully dependant on the pilot, however, required a minimal visual acuity of 0,7.

In cooperation with the Lufthansa we performed similar tests on a commercial aircraft (B 747). In contrast to a Tornado cockpit, where the individual indicators are relatively clearly arranged, the cockpit of a B 747 is much more sectionalized with regard to the available space. The 8 test subjects were pilots between 48 and 54 years of age and showed a distinct presbyopia. All pilots were equipped with optimal correction glasses appropriate their presbyopia, which had been worn at least for 2 months regularly to get used to them. At first only glasses of VARILUX type were used. The visual acuity was reduced with Bangerter foils. All test subjects had a corrected visual acuity of at least 1,0. The pilots participating in the study conducted a total of 21 test flights of 10-15 min. duration each. The tested minimal visual acuity levels were between 0,1 and 0,5. The simulator program was conducted under no-wind-conditions at a visibility of 2.500 m and a cloud base of 1.000 feet. First step of the simulator program was looking through the check lists. All routine actions were accomplished. Then a manually operated ADF-approach was carried out and various emergency situations were proved, for instance an unexpected moving object on the runway. The results of our studies revealed a minimal acuity level of 0,4 to be able to make at least rough interpretations of the charts but only when using an additional spot light. Even a visual acuity level of 0,5 did not allow the reliable reading of fine details of the approach charts. On the other hand the JNS coordinates could already be entered at a visual acuity level of 0,3. Even at a visual acuity level of 0,5 the DME could only be interpreted. This was also true for the readability of the fuel gauge indicator and the hydraulic system. A visual acuity level of 0,3 barely allowed the reading of the air speed indicator, heading indicator and altimeter. This would approximately be the minimal visual acuity level required for landing an aircraft under extreme emergency conditions. This limit would only be true for an approach which is completely familiar to the pilot because exactly the double visual acuity level is required for reading the indispensable approach charts, and this should basically constitute the value of the minimal visual acuity in case of an emergency. An uncorrected visual acuity level of 0,3 certainly is not sufficient for safely flying and landing aircraft under complicated conditions. This leads to the question whether it is helpful to specify the uncorrected visual acuity in standards. In fact, such uncorrected visual acuity levels should allow safe operation of an aircraft, and in this case, however, they should be set much higher than it has been the practice. If we completely do without limits for the uncorrected minimal visual acuity we at least should have limits for the correcting glasses. Such a new procedure would require that these correcting glasses, if required, are permanently worn during flying operations.

In this case more attention needs to be extended on the specific design of spectacle frames than is presently the case for pilot's glasses. Furthermore "human factor design" is needed not only in the arrangement of the pilot's seat, in conformance with body shape of the seatbelts, in the cockpit air conditioning system but rather also in the logical and optical arrangement of instruments and operating controls in such a way that also the senior presbyopic pilot is able to safe operating his aircraft without wearing complex special purpose glasses.

For the tower controller who has to observe the air space and the apron the requirements of the minimal visual acuity should be similar to class I pilots. Limits for correction values of the glasses are not important.

In our studies we only examined air traffic radar control personnel. In cooperation with the Federal Air Traffic Control Agency our studies were performed at the radar simulator of the Munich Training Center. The average distance between the controller's eye and the display ranged from 70 to 90 cm. Further technical details of the Telefunken-Monitor SIG 3000l, that was used for our studies: Image repetition frequency: 30-60 hz. Every 10 sec the target position is relocalized. The size of a normal target label is 2,5 mm, in case of an emergency designation 3,5 mm, corresponding to 9,5-11,5 angular minutes.

11 tests subjects took part in the study, 2 in the age about 30 years and 9 in the age about 50 years, with adequate experience in flight control performance. All test subjects had a corrected or uncorrected visual acuity of at least 1,0. Similar to our tests with pilots the visual acuity was reduced by defined blurring the test subject with "Bangerter foils". The reduced visual acuity was controlled before and after a test for each eye separately. Using different "Bangerter foils" we achieved a defined reduction of the visual acuity between 0,5 and 1,0. During the 15 min. simulator run 5 different critical events had to be identified. We differentiated 3 categories of recognition:

1. Indication of danger immediately recognized
2. Indication of danger delayed but without serious consequences recognized
3. Indication of danger not or too late recognized

The following typical indications of danger had to be recognized:

1. Target label with ident mode (blinking)
2. Change of target label with and without transponder code
3. Change of target label to emergency indication
4. Loss of target
5. Repetition of danger indication with different targets.

As expected the failure rate of each test person increased by reducing the visual acuity. We found a great variation between different test persons. For example an older test person with a reduced visual acuity to 0,5 recognized all 5 indications of danger without any delay while other test persons with unblurred visual acuity of at least 1,0 did not recognize 1-2 indications of danger. The visual acuity in the examined range seemed not to be the only important factor for safe radar control performance. Also professional experience and mental awareness are playing an important role. From our results we conclude that a visual acuity of 0,7 and a correction limited to ± 5,9 dpt (similar to class III) are sufficient for a save radar air control performance. In the future also colour discrimination becomes more important using new radar monitoring systems with colour coded informations on high resolution displays. Further studies on this new field are under investigation and we expect to present additional results on the next AGARD Meeting.

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PERFORMANCE de TRACKING et INFLUENCE du CHAMP de VISION

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Résumé:

La vision en champ visuel limité devient habituelle avec l'emploi de systèmes optroniques montés sur le casque. Pour évaluer l'influence de ces dispositifs sur la performance des opérateurs, les effets de plusieurs niveaux de restriction visuelle sur une tâche de tracking visuo-manuel et sur la coordination oeil-tête ont été testés.

La performance est modérément dégradée quand le champ visuel disponible est petit (20°), sans etre améliorée en champ intermédiaire (70°). L'origine de cette dégradation doit être recherchée dans la mise en jeu de mécanismes adaptatifs neuro-sensoriels nécessités par la restriction du champ plutôt que dans les astreintes biomécaniques imposées par l'amplitude du mouvement de cible. Cet aspect est conforté par l'analyse des modifications de la coordination oeil-tête liées à la forte restriction du champ.

1 Introduction

La situation de vision avec un champ limité devient de plus en plus fréquente en milieu militaire, avec l'utilisation de dispositifs optroniques associés aux systèmes d'armes. Certains de ces dispositifs sont montés sur le casque de l'opérateur. Il peut alors s'agir d'une restriction physique, comme celle résultant de l'emploi de dispositifs d'aide à la vision nocturne, ou d'une restriction "fonctionnelle" liée à l'emploi d'un viseur de casque. Sur le plan physiologique, un double problème est posé:

- la vision périphérique intervient dans les processus d'orientation spatiale. La déprivation du champ visuel périphérique provoque une situation préoccupante pour la conscience de la situation. LEIBOWITZ soulignait il y a quelques années que la conduite de nuit était particulièrement dangereuse car les données d'orientation liées à la vision périphérique était conservées alors que la vision centrale était dégradée. A l'heure actuelle, avec les dispositifs de d'aide à la vision nocturne pour les hélicoptères et les avions, la situation est inverse. La vision centrale est correctement maintenue, mais au prix d'une disparition des références d'orientation de la vision periphérique.
- la limitation du champ de vision amène également des perturbations importantes en termes de coordination oeil-tête et sollicite fortement la plasticité des sous systèmes impliqués dans cette activité (GAUTHIER, 1987).

La présente étude avait pour objectifs de tester les effets de l'amplitude du champ de vision dans deux types de tâches, poursuite visuelle simple et poursuite visuo-manuelle, dans différentes conditions d'excentricité de la cible. Dans un premier temps, nous avons considéré la performance réalisée en tracking manuel, puis nous sommes intéressés aux modifications du couplage oeil-tête enregistrées dans les différentes configurations testées.

2 Méthodologie

2.1 Dispositif expérimental

Il comprend un siège fixe sur lequel le sujet assis est fermement maintenu par un harnais thoracique. Les mouvements de sa tête sont libres.

Un projecteur laser Hélium-Néon est monté sur un affût mobile autour d'un axe vertical proche de l'axe de rotation de la tête. Il projette sur un écran hémisphérique une cible ponctuelle rouge de 1/4° environ. De plus, le dispositif permet la projection d'un réticule annulaire, commandé en vitesse par un joystick placé entre les genoux du sujet. Le sujet a pour tâche de maintenir le réticule autour de la cible en mouvement. Les écarts instantanés cible réticule sont enregistrés au cours de chaque essai. Ils permettent de caractériser la performance réussie par deux indices:

l'écart quadratique moyen E.Q.M. (Root Mean Squared Error - R.M.S. error)
l'écart maximum instantané E.M.X. recueilli au cours de l'essai.

Un dispositif porté par la tête permet d'appliquer une restriction du champ de vision au moyen de disques perforés ajustés avant le début des essais.

On recueille pour chaque essai les mouvements oculaires par Electro-Oculo-Graphie (E.O.G.) et les mouvements tête autour de l'axe vertical par un système potentiométrique.

2.2 Protocole

2.2.1 Première série expérimentale

Dans une première série d'expériences, les sujets ont eu à accomplir une tâche de tracking visuo-manuel sur une cible se déplaçant selon un mouvement horizontal de grande amplitude (± 85°), suivant une loi cosinusoïdale. La cible a été présentée au sujet selon trois vitesse (0.5 rd/s, 1.0 rd/s, 1.5 rd/s), l'ordre des vitesse des essais successifs étant aléatoire. Deux conditions de champ de vision ont été étudiée, champ libre et restriction binoculaire de champ de vision (20°). Chaque niveau de restriction faisant l'objet d'une session expérimentale.
Ces résultats ont été comparés avec une condition de référence en vision champ libre, sans aucune tâche de tracking manuel.

2.2.2 Seconde série expérimentale

Dans une seconde série expérimentale, les sujets ont eu à exécuter une tâche de tracking similaire. Trois amplitude crête du mouvement ont été utilisées (45°, 67°, 85°), tandis que la vitess crête de la cible était toujours maintenue à 0,5 rd/s. Trois niveaux de restriction du champ de vision (20°, 70°, champ complet), ont été explorés faisant chacun l'objet d'une session expérimentale.
Avant chaque série expérimentale, les sujets ont reçu un entraînement jusqu'à obtention d'une performance stable en plateau.

3 Résultats

3.1 Performances

3.1.1 Résultats de la première série expérimentale

Sur la figure n°1 sont portées les moyennes, tous sujets confondus, des E.Q.M., figurés par un cercle, et les E.M.X. figurés par un carré. La vision libre est figurée en clair, la vision restreinte en noir. En abscisse sont indiquées les trois vitesses testées dans les deux sens.

L'analyse statistique des résultats montre une dégradation significative de la performance quand la vitesse de la cible augmente. Par ailleurs, ils montrent aussi que la restriction de la taille du champ de vision n'est significative que pour les vitesse les plus élevées.

A l'issue de cette expérimentation, il apparaissait que que la restriction du champ de vision periphérique pouvait affecter une tâche psychometrice effectuée en vision centrale. On peut penser que cette dégradation est liée à la sortie hors du champ visuel soit de la cible, soit de l'élément contrôlé. Cependant, les E.M.X., qui ne constituent pas habituellement un indice pertinent de la performance, se sont toujours tenus en deçà des limites des 20° du champ disponible. De plus, aucun sujet de l'expérience n'a rapporté de perte visuelle de la cible ou du réticule annulaire de visée. On peut donc penser que la cause de la dégradation de la performance liée à la restriction de la taille du champ de vision est due a une contrainte créée par la modification du couplage oeil-tête.

3.1.2 Résultats de la seconde série expérimentale

Sur la figure n°2 sont figurées les valeurs en degrés des indices de performance E.Q.M., rangés selon l'excentricité de la cible. L'analyse statistique des valeurs n'a pas mis en évidence de dégradation de la performance liée a l'excentricité de la cible.

Sur la figure n°3 sont reportés les mêmes indices, en fonction de la dimension du champ visuel. L'analyse statistique de nos résultats montre une différence significative entre la performance réussie en champ libre et la performance en champ très étroit (20°). Dans les conditions expérimentale présentées, l'exploitation statistique des résultats obtenus pour la performance de tracking manuel donne des résultats ambigus pour ce qui concerne l'influence de l'extension du champ de 20° à 70°. Cette extension n'apporte pas d'amélioration significative de la performance. Inversement, la réduction du champ de vision de champ libre à 70° ne la dégrade pas significativement.

3.2 Coordination Oeil-Tête

Si on considère tout d'abord la condition champ libre comme une condition de référence, l'examen des mesures des mouvements de la tête et des yeux montre des différences selon que le sujet exécute ou non simultanément une tâche de tracking visuo-manuel.

Le couplage oeil-tête relevé au cours d'une simple poursuite visuelle en champ libre est illustré sur la figure n°4. L'amplitude du mouvement oculaire est ±10° environ pour un mouvement de regard de ±85°. La **FIXATION** (i.e. différence instantanée entre la position de la cible et la position du point de regard) est proche de 0°. Quand le même sujet, dans la même condition de vision champ libre, exécute simultanément une tâche de tracking visuo-manuel (figure n°5), on constate que le tracking est effectué au prix d'une forte diminution de l'amplitude du mouvement de la tête compensée par un mouvement oculaire de plus grande ampleur, puisqu'il atteint 30° environ. A droite de la figure est affiché le tracé de l'écart instantané cible-réticule. La ligne droite indique que le réticule a été parfaitement maintenu sur la cible pendant l'essai, presque jusqu'à la fin. Cet exemple concerne les essais portant sur des cibles très excentrées, mais les mêmes tendances sont trouvées sur des cibles de moindre excentricité..

L'effet de la restriction du champ visuel apparait au cours de la tâche de poursuite dès le premier niveau de restriction: La figure n°6 montre un exemple de poursuite visuelle simple exécutée en vision champ libre par un autre sujet. L'excentricité de la cible est ±67°. L'introduction d'une restriction du champ de vision à ±35° (figure n°7) provoque une nette diminution des mouvements oculaires. Notez cependant que le mouvement observé en condition champ libre sur la figure n°6 est physiquement compatible avec le champ de vision disponible dans cette configuration. Sur la partie gauche de la figure, les pointillés représentent les limites du champ visuel. Elles sont calculées relativement à la position de la tête, augmentées ou diminuée de la valeur de la taille du champ de vision (ici: 35°).

La figure n°8 montre les conséquences d'une forte restriction du champ visuel (±10°). L'oeil est quasi immobile dans l'orbite pendant la poursuite, tandis que la tête porte le regard, qui reste centré au milieu du "tube" de vision.

Les figures N°9 et 10 résument les différentes mesures de positions oculaires à différents instants de chacun des essais, selon la tâche effectuée. La figure n°9 décrit les positions moyennes des yeux en fonction de l'instant de la mesure pendant l'exécution d'une simple poursuite visuelle. Les mouvement observés en champ libre y sont inférieurs à 20°. La figure n°10 les décrit pendant l'exécution d'un tracking visuo-manuel. Les mouvement oculaires observés y sont de plus grande amplitude, mais restent, même en vision champ libre, inférieurs à 30°.

4 Discussion

4.1 Perturbations du couplage oeil-tête et viseur

La tâche de tracking utilisée est une "poursuite" (Poulton, 1974), c'est-à-dire que les deux éléments visuels de la tâche sont mobiles dans le champ. La plupart des dispositifs de visée montés sur la tête font l'économie de la boucle de contrôle manuelle du réticule. Il s'agit donc, dans ce dernier cas, de tracking compensatoire où le réticule occupe une position fixe dans le champ, le contrôle appliqué par l'opérateur s'exerçant sur la position relative de la cible.

D'importantes modifications du couplage oeil-tête sont très clairement apparues entre les différentes situations expérimentales utilisées lors de cette étude. L'un des points les plus nets pendant la tâche de tracking visuo-manuel est la recherche d'une plus grande stabilité de la tête, associée à une plus grande mobilité de l'oeil. Les conditions de restriction du champ de vision contrarient profondément ce besoin. Il faut remarquer ici la similitude qui existe avec une situation de viseur clair où l'oeil doit prendre une référence fixe dans le champ de vision, quelle que soit alors l'amplitude de celui-ci.

Les conditions de champ de vision utilisées au cours de l'étude amènent à une double tâche: mettre la cible en position relative fixe dans le champ de vision et aligner le réticule. Sur ce point le tracking compensatoire effectué avec la tête avec un viseur semble une solution plus adaptée puisqu'il supprime une boucle de contrôle. Cependant ce mode de tracking, s'il est associé à une tâche manuelle de pilotage, peut aussi se révéler pénalisant sur le plan de la performance, puisqu'il implique des caractéristiques de déplacement de la tête contraignantes.

L'utilisation de viseurs très grand champ, comme ceux évoqués pour le projet américain de cockpit virtuel, seraient incohérents avec le mode de tracking compensatoire. La poursuite avec un réticule mobile commandé manuellement pourrait alors constituer une solution. Sur le plan de l'oculomotricité et du couplage oeil-tête, l'optimisation de tels viseurs nécessite vraisemblablement de pouvoir utiliser la direction du regard pour la fonction de désignation. Notons au passage que les amplitudes de mouvement oculaires rencontrées au cours des poursuites sont cohérentes avec les performances attendues des systèmes de mesure en cours de développement.

4.2 Dimension du champ de vision

4.2.1 Effets sur la coordination oeil-tête

La présente étude s'intéresse à un champ de vision binoculaire circulaire. Cependant, du fait de l'exécution de la tâche dans un plan horizontal, l'analyse des résultats ne peut porter que sur des considérations liées à l'extension latérale du champ.

Le problème de la dimension du champ des systèmes optroniques montés sur casque peut être considéré comme crucial. Outre les difficultés techniques rencontrées dans la réalisation de systèmes "grand champ", le coût des viseurs présente une nette tendance à augmenter sur un mode exponentiel, en fonction de l'amplitude du champ requis. D'autre part, la dimension du champ conditionne également l'encombrement du système et la distance oeil-viseur. Le problème de l'encombrement est particulièrement important dans les avions d'armes, du fait de l'exiguïté des cockpits et des évolutions sous facteur de charge.

Dans cette optique, les résultats obtenus avec les champs de 20° et de 70° au cours de notre étude ouvrent une voie de réflexion intéressante. On constate que les modifications du couplage oeil-tête induites par la restriction du champ sont, d'une manière relative, assez proches dans les deux cas. En particulier, la restriction provoque un mouvement de la tête de grande excentricité, proche de celle de la cible, à la source d'une contrainte biomécanique par rotation forcée du cou.

Pourtant, le champ de 70° permet d'effectuer des déplacements de l'oeil au moins équivalents à ceux observés en vision libre. Sur ce point précis, l'extension du champ de vision n'apporte qu'une amélioration relativement faible dans le sens d'une stratégie plus naturelle de coordination oeil-tête. Cette amélioration ne s'effectue en aucun cas en proportion des possibilités offertes par le champ à 70°.

4.2.2 Effets sur la performance

L'absence d'effet excentricité de la cible sur la performance permet d'écarter une origine purement biomécanique de la modification de performance. Mais la présence d'un effet lié à la taille du champ visuel permet d'envisager un effet neuro-sensoriel. Les résultats obtenus suggèrent que la dégradation des capacités avec la réduction du champ de vision ne se fait pas selon une loi harmonieuse. Il semble ici exister un effet de "bord" qui conditionne les modalités d'adaptation du couplage oeil-tête et, peut-être, de la performance de tracking.

Il existe, bien sûr, beaucoup d'autres éléments qui interviennent dans le problème du dimensionnement du champ des viseurs. Les premiers résultats obtenus ici permettent néanmoins de faire l'hypothèse qu'il serait, peut-être, plus "payant" de s'intéresser au contenu du champ qu'à son extension de quelques dizaine de degrés.

Ces résultats méritent cependant d'être confirmés par des études portant sur des cibles se déplaçant aléatoirement et sur deux degrés de liberté.

5 Conclusion

Les résultats obtenus au cours de cette étude sur l'effet de la restriction du champ de vision sur la performance de tracking manuel montre l'existence d'une dégradation de la perfor mance associée à la restriction du champ. Cependant cette dégradation reste dans tous les cas modérée. On constate de plus une réorganisation des mécanisme du couplage oeil-tête au cours de la poursuite. Il n'existe, à ce niveau, que relativement peu de différence entre les champs de 20 et 70°, par rapport à l'extension des possibilités offertes dans ce dernier cas.

L'exploration de différentes excentricités de la cible permet d'écarter l'hypothèse de la contrainte biomécanique à l'origine de la dégradation de la performance. Il semble qu'il soit nécessaire de s'orienter vers des mécanismes neuro-sensoriels, pour expliquer la baisse de performance en vision restreinte. Parmi ces mécanismes, on peut avancer la perturbation liée à l'augmentation de la mobilité de la tête avec la restriction, qui contrarie le besoin de stabilité pour exécuter la tâche manuelle.

Sur le plan pratique, l'optimisation de viseurs très grand champ pour la désignation nécessite sans doute l'utilisation de la direction du regard. Par ailleurs, l'extension du champ des viseurs de casque à des valeurs intermédiaires peut apparaître discutable, du moins au regard des considérations de coût et d'amélioration du couplage oeil-tête.

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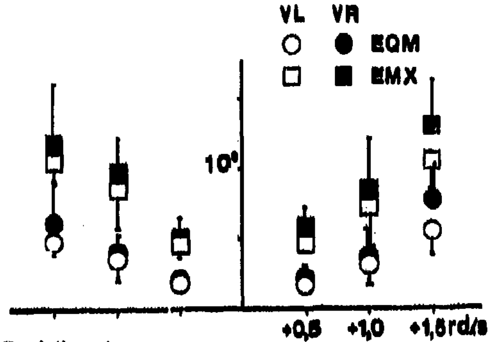
Figure 1



Evolution des Moyennes des Performances selon le Mode (VL ou VR) et la Vitesse (-1,5 à +1,5 rd/s)

Figure 2

PERFORMANCE de TRACKING
rapportée à l'amplitude du mouvement
de la cible

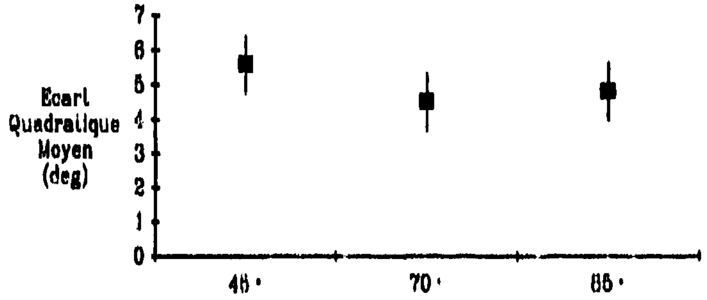


Figure 3

PERFORMANCE de TRACKING
Influence du champ de vision

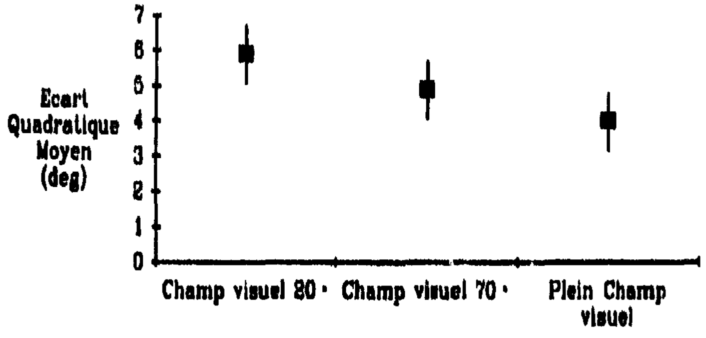


Figure 4

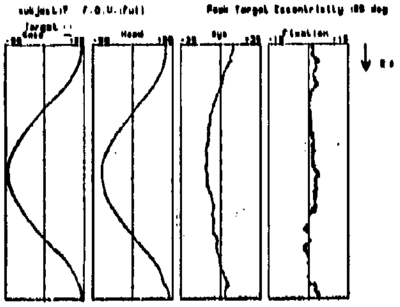
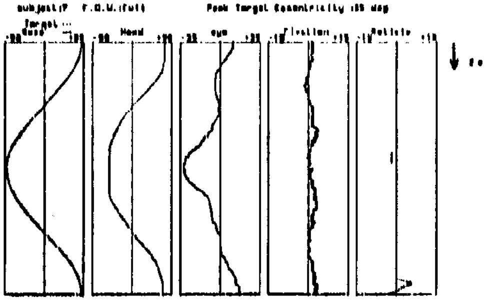


Figure 5



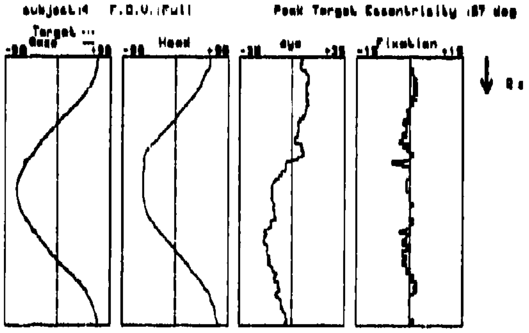


Figure 6

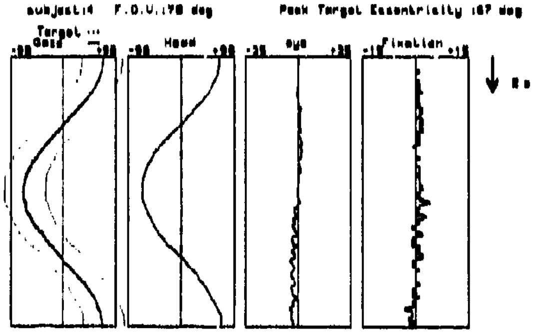


Figure 7

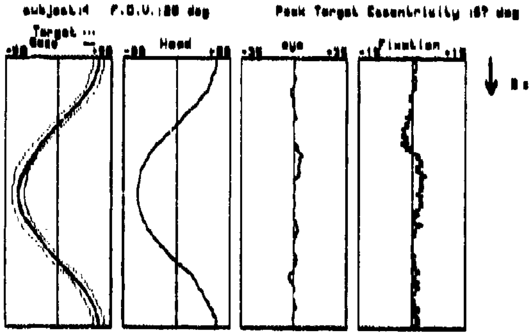


Figure 8

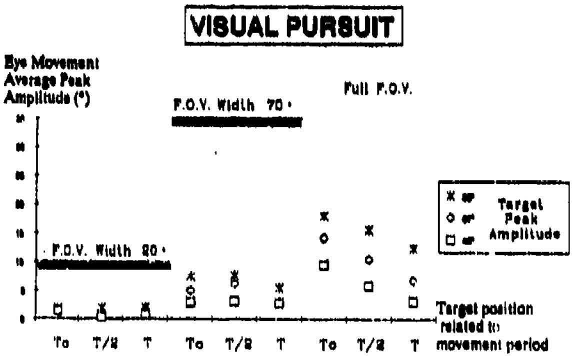


Figure 9

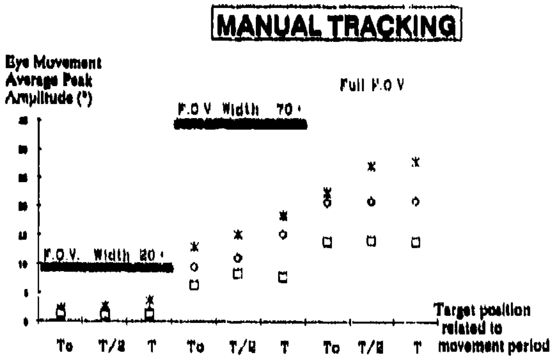


Figure 10

NEUROPHYSIOLOGICAL CORRELATES OF INFORMATION PROCESSING ABILITIES DURING DIVIDED ATTENTION SITUATIONS IN AIR TRAFFIC CONTROLLERS

by
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Summary

The aim of the study was to elucidate which relationships exist between arousal, cognitive functioning and generalised expectancy of control in a group of air traffic controllers (ATC), in conditions of single and dual tasks. Furthermore, under the same conditions and based on performance outcome, it was attempted to evidentiate eventual differences in cognitive functioning which could be related to the diversity of professional ATC skills.

Our data show that arousal is increased in the dual-task, N2 peak latency is positively correlated to arousal in both tasks, correlates inversely with perceived control in the single task and relates inversely with activation in the dual task, and adjusted arousal correlates with perceived control. Finally, N2 peak latency appears to be sensitive to ATC skill.

Introduction

Air traffic controllers (ATC) are individuals who are forced to deal with cognitively complex situations for professional reasons. Using the parameters of information processing theory (pattern recognition, stimulus evaluation, response selection, observable behaviour), it can be supported that ATCs perceive a set of stimulations which are simultaneously codified and subsequently classified; thus, the most correct response in a given situation will be chosen on the basis of the preselected data organisation. ATCs are subdivided into three categories:

1) tower controllers;
2) approaching controllers; and
3) area controllers.

The latter, although being assigned a particular duty, have also professional qualities to deal with tower control and airport approaching; thus they represent the subgroup of ATCs with the broadest capacity of intervention on air traffic. Therefore, it can be said that the area controller acquires an experience which allows him to resolve the entire range of problems posed by air traffic control. The question that might be asked at this point, is whether acquiring this experience is translated into a different information processing capacity; does knowing how to deal with situations characterised by a higher number of variables results to changes in the choice of operational strategies, based on codification and classification of joining stimuli?

If a laboratory paradigm is used, it is possible to focus on more than one levels of investigation to try to respond to this question. A first level to focus regards the evaluation of subjective behaviour in defined performance tasks. A second level concerns the analysis of stimulus-evoked cerebral bioelectric activity associated with the ongoing performance, which permits to explore perceptive mechanisms. A third level is represented by the evaluation of the level of arousal (tonic state) and of the degree of activation (phasic reaction) in various situations; in this way, it is possible to measure the physiological cost of the cognitive functioning. Finally, if we assess the perceived control of reality expressed by the subject, we may test response outcome expectancies based on passed experiences. By correlating data stemming from the above levels, it is perhaps possible to extrapolate more precisely on the relationships between psychometric parameters and behaviour, modulating in the same time such relationships by means of informations on cognitive functioning and state of individual activation (1). Analysing in detail some aspects of the above, it should be emphasised that cerebral evoked potentials represent a means of studying information processing theory as applied on perception. Thanks to defined experimental paradigms, the electrocortical correlates of some initial phases of information processing have been identified (2):

1) selective attention is correlated to the negativity of processing (post-stimulus latency from 50 to several hundred msec) (3), otherwise termed negative difference wave (Nd) (4); often, attention modifications are correlated to the effect on the N1 compponent (post-stimulus latency 100-140 msec)

because the latter tends to overlap to the negativity of processing (5,6).

2) The N2 component (post-stimulus latency of about 200 msec) is subdivided into a mismatch negativity (N2a), correlated to physical changes of the stimulus (6,7,) an N2b subcomponent, related to expectancy mismatch (8) and an N2c subcomponent, which can be related to the classification of the stimulus (9). Overlapping with N2A, is the the negative deflection NA, corresponding to the phase of pattern recognition (stimulus codification) (9).

3) The P3 component (post-stimulus latency 250-500 msec) would relate to working memory up-date (10) and to global evaluation of the stimulus situation (2).

In the dual task paradigm (when the subject is asked to follow two inputs) (11) and in the case of the "oddball" paradigm, where one of the required perfomances is the identification of target stimuli interspersed in a series of standard stimuli, the analysis of cerubral potentials evoked from target stimuli permits to evidentiate the particular sensitivity of the P3 component to the quantity of perceptive resourses directed at detecting the target stimulus (2). This means that the more difficult the concomitant task, the greater the P3 wave change (12), which amplitude will diminish as a function of the quantity of perceptive resourses withdrawn from the subject. On the other hand, it is common sense that the performance is better when only one task is undertaken and especially when the cognitive load is less, pointing at the presence of a defined and limited quantity of energetic resourses (13).

In information processing theories, a central aspect is represented by the idea that the performance of a given task depends on the employed processing strategies and on the degree of effort or on available resources (14). Processing structures compete for those limited resources and this explains the performance deficits observed in the dual task paradigm (11). To assess the quality of information processing, it is necessary to know the organism's quantity of available resources. The physiological energy level (arousal), which is translated into both behavioural and psychic energy, is determined by the entity of bodily metabolic activity and is expressed by brain bioelectric activity (15). The arousal level of an organism indicates the quantitative limits of a behavioural response and, in the same time, its emotional state. The conscience level and emotional arrousal are intimately related (15). This entails that when a dual task paradigm is used, it is important to analyse not only the activity of the processing structures which compete for available resouses, but the subjective emotional state as well. This is suggested by the time-known inverted U-shape relation between arousal level and performance (11). The arousal can be assessed in three ways (1):

1) As a tonic state; in this case it is analysable by means of serial sampling of physiological-biochemical and behavioural parameters, and parameters related to self-evaluations during the steady-state phases.

2) As a phasic reaction correlated to events; in this case it is subject to evaluation on the basis of psychophysiological variable modifications (e.g. heart rate) versus a base-line condition.

3) As a trait, i.e. reactivity proneness; in this case the relatively stable predisposition to show higher degrees of activation and/or reaction under certain experimental conditions is studied by means of questionnaires.

As indicated in this last point, the subjective emotional state reflected on the arousal level depends on certain personality characteristics (16) and also on how the subject faces reality (17). Whereas the correlations between physiological reactivity and personality questionnaires are modest and in many cases nonsignificant (1,17), the importance of the role of psychological variables, such as perception of control and outcome expectations, is increasingly recognised as being in a position to explain in a more complete and refined way several observable behaviours and their underlying physiological reactions (17,18). For example, a recent study by Ullsperger et al. (19) showed that P3 wave amplitude increases with increasing task complexity; this appears to correlate with the subject's evaluation of task difficulty. This evaluation is based on a subjective reference system calibred on the experience of how much energy is necessary to correctly resolve a basic task. This stresses the importance of subjective evaluation on the degree of activation, which is in turn responsible of some observed modifications of evoked potential components. In this light, a construct which revealed to be interesting for its implications is that of Rotter's locus of control (20). This refers to the generalised expectancy tending to perceive the positive reinforcement of a subject's actions either as depending on his/her own behaviour (internal locus of control) or as the result of the action of forces which are beyond individual control (external locus of control) (21). In the above definition, the term generalised expectancy refers to the concept that expectancies are transferred from one context to another on the basis of previous experiences. Thus, generalised expectancy increases with increasing individual experience with respect to a given situation (21). Therefore, an individual who perceives reinforcement as depending either on his/her own actions or on his/her relatively permanent characteristics, will present generalised expectancies of internal control, in other words the perception that events are under his/her own control. Furthermore, in the construct of the locus of control, two dimensions are contained (22): locus of causality, relative to the establishment of a stimulus-response contingency ("the responsability for what is happenning is mine") and controllability ("is the event controllable by myself or not?"). This last aspect is particularly interesting, because it influences coping modalities. For example, individuals with a prevalence of internal locus of control appear to adopt a behaviour which is centred more on the task than on the emotion (23), thus they perceive less stress and perform better. To summarise, if the subject believes himself to be capable to deal with a given situation, the strategy he utilises in resolving the inherent problems is that of concentrating on the specific problem (increased arousal with no reported stress (18)). If the subject believes himself not to be able to completely control the situation, then the coping modality is based on the management of emotion (increased arousal, but only when the goal valence is high; this is reported as stressful (17)).

In conclusion, cognitive evaluation results in energy mobilisation (which entity is a function of the goal valence), which will or will not be expended for the solution of the problem posed by the event depending on the subjective expectancy of control.

Aim of this study, conducted on ATCs involved in a dual task, was to clarify some problems:

1) Which is the relationship between arousal and cognitive functioning, as explored through the N2 component of cerebral event-related potentials (ERP)?

2) Which is the relationship between control expectancies (perceived control) and cognitive function (N2 of ERP), when the effect of the arousal level is excluded?

3) Which is the relationship between arousal and perceived control if intersubjective differences of cognitive functioning (N2 of ERP) are eliminated?

4) Are differences in ATC skill in handling cognitively complex situations reflected on cognitive functioning (N2 of ERP) in the context of a dual task experimental paradigm?

Materials and Methods

The study has been divided in two parts:

a) We attempted at elucidating which relationships exist between arousal, cognitive functioning and generalised expectancy of control in a group of ATCs, in conditions of single and dual tasks.

b) Under the same conditions, based on performance outcome, we tried to single out eventual differences in cognitive functioning which could be related to the diversity of professional experience.

The dual task to which the subjects have been subjected consisted in the identification of target acoustic stimuli randomly inserted in a series of standard acoustic stimuli (oddball paradigm) and an arithmetic task of serial subtractions. The results regarding the dual task situation have been compared with those regarding a single task condition, in which subjects were simply required to identify target acoustic stimuli in a similar to the previously mentioned oddball paradigm. The evaluation of the arousal was carried out through monitoring heart rate during the entire session. The evaluation of cognitive functioning was carried out by considering the N2 peak latency of the cerebral evoked potentials associated to acoustic target stimuli. The choice fell on the N2 component for the following reasons:

- it is associated, as in the case of the P3 component to target stimuli (7);
- by increasing reaction time, N2 and P3 latencies increase in an approximatively measurable way (7);
- N2 reflects, as we described previously, a decisional process, correlated to sensory discrimination of expected stimuli (detection of physical changes of the stimulus and classification of the stimulus) (24);
- the N2 component is responsible for, or initiates in parallel, the neural activity which relates to motor responses and to reflex processes in the P3 component (25);
- N2 is sensitive to the nature of the classification task (24).

Psychometric evaluation focused on analysing state anxiety before and after the experimental session, in order to have indication on the initial level of anxiety, on its eventual modifications during the course of the session and on its relationship with the recorded arousal. The determination of the locus of control allowed us to analyse the role of perceived control on the tonic state of the arousal and on the type of phasic reaction under conditions of simple and dual task; furthermore, it permitted to test the significance of perceived control on the process of sensory discrimination of expected stimuli (N2 peak latency) in both conditions.

Sample

Twelve healthy, right-handed male ATCs volunteered to participate to the study (age, mean 29.58; S.D. 3.8). Six subjects, skilled in area control were classified as skilled, whereas the remaining 6, who only had tower and/or approaching procedure experience, were classified as less skilled. Moreover, 6 non-ATC subjects of comparable age and socio-cultural level (non-skilled) were used as the control group, in order to reveal more clearly performance and cognitive function differences in dual task conditions (point (b) of the experimental design). Because of technical problems inherent to heart rate recording in 2 ATCs of the less skilled group, the analyses regarding arousal were carried out on 10 TCAs.

Data collection

Heart rate has been recorded by positioning two pregelled Ag/AgCl electrodes at the 2nd intercostal space on the left parasternal line and at the 5th intercostal space on the left hemi-clavicular line. An Oxford Medilog 8000 apparatus has been used for recording on a TDK-SA 90 tape (high bias, 70 microsec EQ).

Cerebral bioelectric activity has been recorded by means of Ag/AgCl electrodes, positioned on 17 leads (F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, O2); for the purposes of this study, only the activity recorded at Cz has been considered, because the latter is one of the leads where the N2 component is best visualised (7). Ocular movement monitoring has been carried out by placing an Ag/AgCl above the right supraorbital ridge. Reference was linked bimastoids. The time constant was 0.3 sec; the high frequency response was 50 Hz. Thanks to a slight abrasion, the impedence was 2 Kohm. A notch filter was introduced. Sensitivity was 5 microVolts per cm. Cerebral ERPs were obtained by means of acoustic tones (intensity 72 dB HL; plateau 30 msec) presented binaurally through earphones. Target stimuli (frequency 1000 Hz) were randomly interspersed between the standard stimuli (frequency 1500 Hz). The number of target stimuli ranged randomly 14-16; the probability of their appearance was about 1 every 8 standard stimuli. The interstimuli interval ranged randomly 1000-3800 msec.

To evaluate state anxiety we used the 20-item X-1 form of the State-Trait Anxiety Inventory (STAI X-1), a 40-item, self-rated questionnaire (26). To analyse control expectancies, Rotter's Internal-External locus of Control Scale (LOC), a self-administered scale, was used (20,21).

Procedure

The experimental session took place between 09.00 h and 14.00 h; it consisted in the following phases:

1) Arrival at the laboratory; habituation to the setting.
2) Electrode placement for the recording of arousal.
3) Electrode positioning for electrical cerebral bioactivity recording; during this phase, the LOC was filled out.
4) Once the subject was prepared, he sat confortably in an air conditioned, dimly lit and noise-proof environment. After having completed the STAI, the subjects ran 2 trials, each consisting of only 2 target stimuli, so that the subject could learn to identify such stimuli.
5) The single and dual tasks were thereafter presented in a random order, the subject staying with eyes closed; he was asked to count the perceived target stimuli in silence and, in the case of the dual task, to perform simultaneously his arithmetic task (serial subtraction of 7 from a three digit starting number), always silently. The duration of the task depended on the time necessary to present the target stimuli (4-5 minutes).
6) The subject was asked to present the results and was informed on the correctness of his performance; finally, he filled out the STAI X-1 for a second time.

Data processing and statistical analysis

Heart rate has been analysed off-line on the Oxford Medilog 8000 apparatus (time constant 0.1 sec; high frequency cut-off 30 Hz; gain x 2) by two raters blind to the results. The time needed for task performance was subdivided in epochs of 16 sec each; the number of QRS complexes per epoch was thence determined and expressed as beats per minute (bpm). Finally, the mean heart rate has been calculated for the entire duration of each of the two performances by summing data relative to separate epochs (tonic state). The mean bpm value of eight 16-sec epochs has been considered as baseline; for this calculation we chose 4 epochs 30 min and 4 epochs 15 min pre-ERP recording. To evaluate changes in arousal (phasic reactions) during the various phases of the session we calculated percent changes of mean heart rate values with respect to baseline.

Averaging for obtaining ERPs was carried out on-line. Similarly, every ERP underwent smoothing computed on 6 points. The sampling interval was 2.5 msec for a period of 1000 msec post-stimulus. Mean values of responses to target stimuli (ERPs) were considered; the N2 peak latency was separately identified by two raters blind to other results. To identify such latency, we considered the N2 component as the most negative peak comprised in the 200-300 msec post-stimulus interval; furthermore, we tried to confirm our hypothesis on the basis of the spatio-temporal map of the evoked cerebral bioelectric activity. To evaluate the performance on the arithmetical task, we measured the number of operations per minute. Given the reduced numerosity of our sample, we chose to prefer non-parametric statistical analysis, eventually using parametric techniques to confirm our evidence. Intra-group comparisons were made by using the Wilcoxon Matched-Pairs Signed-Ranks test (27) and ANOVA 1-way for randomised blocks (20). For inter-group comparisons, we used the Mann-Whitney U-test (27). To calculate correlation coefficients, we used the Spearman rank test; the significance level of such coefficients was determined through Student's t, which is possible to apply when the experimental sample is equal to or more than 10 subjects (27). The evaluation of performance change in passing from the single to the dual task, was made through the chi-square test (27). We sought for a regression line between the N2 peak latency and arousal (heart beat) so that we could use analysis of covariance and adjust values, thus to exclude the effect of arousal on cognitive functioning and vice versa (28). Finally, we used simple linear regression analysis to evaluate the relationship between arousal modifications (phasic reactions) and cognitive functioning (29). The cut-off point for statistical significance was assumed to be p 0.05, two-tailed.

Results

Dual task performance yielded a highly significant increase in heart rate with respect to base-line (Wilcoxon's rank test, T=0, p 0.01; ANOVA 1-way, F=30.33, p 0..1) and to the single task situation (Wilcoxon's T=4, p 0.02; ANOVA 1-way, F=13.93, p 0.01) (Fig. 1; Tab. I). On the contrary, single-task performance did not induce significant heart rate modifications with respect to base-line (Wilcoxon's T=20, nonsignificant (n.s.); ANOVA 1-way, F=2.18, n.s.) (Fig. 1; Tab.I).

The identification of target stimuli was rendered more difficult by the simultaneous performance of mental arithmetic calculation; the number of errors is significantly higher (chi square=5.041; p 0.05) (Tab. I).

No significant differences were found in the N2 peak latency between the dual and the single-task conditions (Wilcoxon's T=11, n.s.; ANOVA 1-way, F=0.435, n.s.) (Tab. I).

The level of state anxiety did not change significantly during the session of ERP recording (Wilcoxon's T=14; n.s.) (Tab. II).

N2 peak latencies and heart rate were positively correlated during single-task (Spearman's rho=0.821, t=4.067, p 0.01) (Fig. 2) and during dual task performance (Spearman's rho=0.665, t=2.518, p 0.05) (Fig. 3). The application of co-variance analysis and of the method of adjusted Y (28) permitted to evaluate the relationship between the E (external control) scale score in Rotter's test (Tab. II) and the N2 peak latency, excluding the effect of arousal; these two variables were positively correlated during single-task performance (Spearman's rho=0.714, t=2.886, p 0.05) (Fig. 4), whereas during dual task performance, no correlation was evident (Spearman's rho=0.173, t=0.497, n.s.). Adjusting heart rate values as a function of the N2 peak latency (thus excluding from the relation the effect of cognitive functioning by applying the method of adjusted Y) an inverse

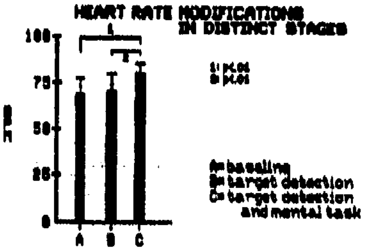

Fig. 1

TAB. I -		single task	double task
Heart Rate	$\bar{X}$	70.365	79.216
	SD	(11.367)	(8.47)
Activation vs baseline (per cent)	$\bar{X}$	3.297	17.251
	SD	(6.704)	(10.968)
N2 Peak Latency	$\bar{X}$	234.75	237.75
	SD	(17.89)	(16.56)
Performance (target det.)		correct: 11 incorrect: 1	correct: 6 incorrect: 6

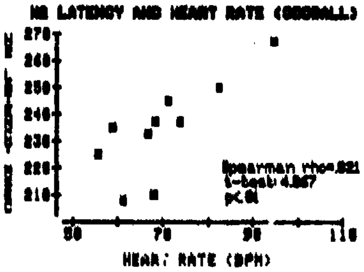

Fig. 2

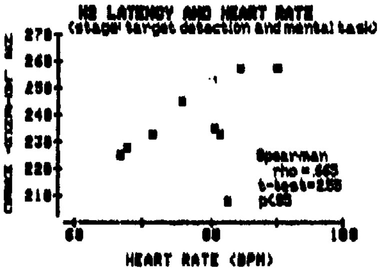

Fig. 3

correlation between adjusted heart rate and E scale scores was apparent, both during single-task performance (Spearman's rho=-0.689, t=-2.689, p 0.05) (Fig. 5), and during dual task (Spearman's rho=-0.745, t=-3.159, p 0.02) (Fig. 6). No correlation was apparent between pre-ERP recording state anxiety, and heart rate at base-line (Spearman's rho=0.441, t=1.39, n.s.), during single-task (Spearman's rho=0.554, t=1.834, n.s.) and dual-task performance (Spearman's rho=0.039, t=0.11, n.s.). Moreover, no correlation was apparent between self-rated state anxiety prior to task performance and degree of arousal modification (activation) with respect to base-line during single- (Spearman's rho=0.2, t=0.577, n.s.) and dual task performance (Spearman's rho=-0.318, t=-0.95, n.s.).

Similarly, no correlation emerged between the E scale scores and activation (single-task: Spearman's rho=0.16, t=0.455, n.s.; dual task: Spearman's rho=-0.222, t=0.644, n.s.). A significant linear regression was instead present (ANOVA 1-way, F=7.81, p 0.05) between N2 peak latency and activation (correlation coefficient=-0.703) only in the dual-task condition (Fig. 7).

In the intergroup comparisons between skilled and less skilled ATCs, no differences emerged when evaluating:
- baseline arousal level (Mann-Whitney's U=6, n.s.);
- arousal level during single-task performance (Mann-Whitney's U=7, n.s.);
- E scale scores (Mann-Whitney's U=11, n.s.).
- arousal level during dual-task performance (Mann-Whitney's U=10, n.s.).
- N2 peak latency during dual-task performance (Mann-Whitney's U=14, n.s.).

The only statistically significant difference in skilled vs. less skilled ATC comparisons regarded N2 peak latency during single-task performance. Skilled ATCs had shorter N2 peak latencies compared to less skilled ATCs (Mann-Whitney's U=3.5, p 0.02). The attempt to clarify which is the role of experience on cognitive functioning (N2 peak latency) in dual-task performance was countered by the fact that only 6 subjects out of 18 performed correctly on both tasks. However, even in this case, an interesting, although non-significant, datum emerged (Tab. III); N2 peak latency was less in skilled ATCs with respect to the other two subgroups, and less in the less skilled, as compared to the non-skilled (non-ATCs).

TAB.II - Mean score and standard deviation on the psychometric tests

STAI X1 pre: 29.9 (SD= 6.556)
post: 28.8 (SD= 5.574)

External Scale : 7.2 (SD = 4.39)
(Locus of Control)

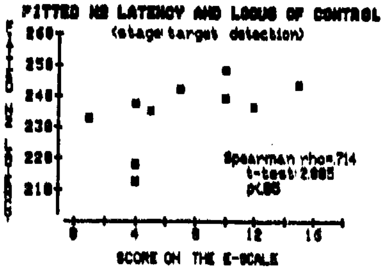

fig. 4

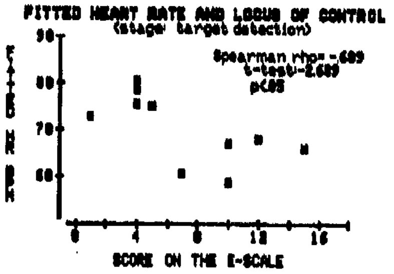

fig. 5

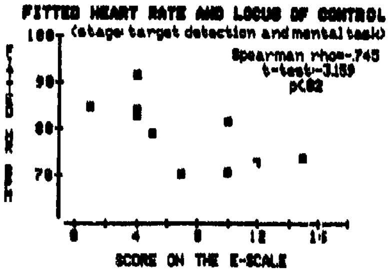

fig. 6

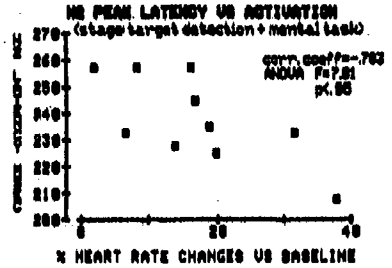

fig. 7

TAB.III - Values of the 6 subjects correctly performing both tasks (target discrimination and mental arithmetic tasks)

	N2 latency (msec)	subtractions per minute	heart rate (bpm)
HIGH SKILL	228	7.5	66.83
" "	232.5	4.84	81.39
" "	245	13.02	75.07
LOW SKILL	257.5	6.40	90
NO SKILL	260	6.12	72.04
" "	262.5	10.02	91.58

Discussion

In this study, we attempted at identifying eventual relationships between cognitive and psychometric variables and experience in complex task performance.

Significant data emerging from this study, are the following:

1) Arousal is increased with respect to base-line only during the dual-task performance.

2) The simultaneous performance of mental computation leads to decreased detection of target stimuli.

3) N2 peak latency is positively correlated to the present level of arousal, both during single- and dual-task performance.

4) When the effect of the intersubjective differences in arousal is excluded, the N2 peak latency correlates inversely with perceived control only during simple target detection.

5) Excluding the effect of the 'cognitive functioning' variable, arousal is positively correlated with perceived control in both experimental phases.

6) The magnitude of activation with respect to base-line is inversely related to the N2 peak latency only in the dual-task phase.

7) N2 peak latency is measure which is sensitive to the degree of ATC experience. It is less in skilled as compared to the less skilled during single-task performance; at the same performance level in the dual-task and within the range of values shown, it is minimal for the skilled, intermediate for the less skilled and maximal in the non-skilled.

The dual task condition determined, as already described in literature (30), an increased arousal and a reduced performance quality on target detection. The necessity to share the available energy between the two tasks, explains such a reduction. The cognitive evaluation relative to the controllability of the experimental situation may explain the different levels of arousal found in this study. In fact, from the present results it may be concluded that the higher the perceived control expectancy, the higher the arousal level in both the single- and dual-task situations. It is probable that individuals with a higher generalised expectancy of control are more activated to confirm their capacity to deal with reality. The physiological cost of a similar cognitive functioning would consequently be higher in individuals exhibiting a higher perceived control. However, the existence of an inverre correlation between the N2 peak latency and perceived control might indicate that subjects having an internal locus of control possess different modalities of facing problems. In fact, individuals with a higher expectancy of control would tend to resolve problems, whereas those with an external locus of control would focus on emotions which are determined by the situations they are confronted with (17). This not only worsens performance, but probably also interferes with learning. This last consideration is based on the evidence of a study by Gaillard et al. (31). These authors observed that practice increases the speed at which stimuli are classified after codification; the effects of practice become evident 200 msec after stimulation and are therefore reflected on the N2 component characteristics. If experience speeds up stimulus quality scanning and results in higher perceived control, then, generalising, we should obtain a reduction in N2 peak latency as a function of the extent of perceived control. Our results support this hypothesis, since this negative correlation occurred in the single-task condition. In the dual-task condition, the activation (phasic reaction) was conspicuous, thus probably obscuring such correlation. To further complicate the picture, is our result of a negative correlation between N2 peak latency and the activation relative to the dual task performance. The existence of a positive correlation between the level of arousal (tonic state) and N2 peak latency in either task conditions appears to indicate a worsening of cognitive functioning when the organism's energy is not directed, through a phasic reaction, at overcoming an environmental challenge.

The importance of experience in information processing is evident if we consider that the process of stimulus quality discrimination is faster in skilled ACTs. Given the small numerosity of our sample it is premature to draw definitive conclusions. Nevertheless, our results hint at N2 peak latency being a means of differentiating between skilled and less skilled or non-skilled subjects and prompt at investigating thoroughly this point.

Conclusions

From a methodological standpoint, this study was an attempt to achieve an integrated approach, in order to explore simultaneously psychometric (locus of control and state anxiety) psychophysiological (ERP and arousal) and behavioural variables (performance). Such an approach is limited by the absence of comprehensive theoretical constructs, comprising all investigational levels. The utility of studies of this kind is to correctly define discriminant functions which could permit to differentiate individual behaviours in different contexts.

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BAISSE DE LA VIGILANCE ET CONSCIENCE DE LA SITUATION DES PILOTES AU COURS DE VOLS LONG-COURRIERS

par

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RESUME

Les variations du niveau d'éveil au cours d'activités monotones ont été montrées par de nombreux auteurs. Dans le domaine aéronautique, au cours de vols long-courriers, ces variations du niveau d'éveil peuvent dégrader la performance et la capacité du pilote à apprécier les événements. Afin d'étudier le comportement des pilotes au cours de ce type de vols, une recherche sur le terrain a été entreprise. Elle a pour objectif d'identifier les phases d'hypovigilance et d'évaluer leurs répercussions sur la performance des pilotes et leur conscience des événements. La méthode repose sur l'utilisation de techniques ambulatoires permettant de recueillir l'EEG, l'EOG, la fréquence cardiaque et l'activité motrice des pilotes au cours du vol, simultanément à une observation de la tâche. Les premiers résultats de la phase préliminaire portant sur huit vols long-courriers sont présentés.

INTRODUCTION

L'évolution des postes de pilotage se traduit par une automatisation de plus en plus poussée des tâches de pilotage et de la gestion du vol. Cette automatisation, par les modifications qu'elle apporte dans le contenu des activités des différents membres de l'équipage contribue à diminuer la charge de travail pendant les phases les plus critiques du décollage, de l'approche et de l'atterrissage, ou encore lors d'incidents, voire de pannes. Dans le cas de vols long-courriers, cette automatisation va par contre exagérer la monotonie du vol de croisière. Dans le même temps, cette évolution entraîne une modification dans la répartition des rôles entre le pilote et l'avion, le pilote étant souvent réduit à un rôle de surveillance.

La monotonie qui résulte de ces évolutions technologiques engendre dans un grand nombre de cas des baisses du niveau de vigilance. Ceci n'est pas spécifique à l'aéronautique et a pu être montré par plusieurs auteurs notamment dans le domaine ferroviaire, que ce soit sur le terrain (1,2) ou dans des études de laboratoires utilisant une tâche de conduite simplifiée (3). Ces fluctuations du niveau d'éveil sont amplifiées, dans le cas de pilotes de vols long-courriers, par des perturbations des rythmes circadiens liées à la fois aux décalages horaires et au travail à horaires alternants (4,5,6,7). Les études menées sur le terrain utilisent des techniques de monitoring ambulatoire afin de recueillir des paramètres physiologiques. Ces études ont permis notamment de mettre en évidence les perturbations du cycle veille-sommeil consécutives aux vols transméridiens et leurs répercussions sur la vigilance pendant les différentes phases de vol. Cependant ces études demeurent limitées dans les conclusions et les applications qu'elles permettent de tirer. Il semble important de les compléter en effectuant une observation de la tâche plus élaborée afin d'identifier de manière précise les tâches susceptibles d'être affectées par des baisses de vigilance et de concevoir des moyens de réactivation, en optimisant par exemple la gestion des cycles activité-repos (8).

Les baisses du niveau de vigilance ont des répercussions directes sur la performance du pilote. Elles affectent à la fois son attention, mais également sa conscience de la situation et des événements qui se déroulent au cours du vol. Ce phénomène d'hypovigilance, lié à la diminution des sollicitations sensorielles et de la charge de travail du pilote peut altérer la qualité de la réponse du ou des pilotes, notamment lors de situations critiques. Dans le but d'évaluer la variabilité du niveau d'éveil des pilotes et d'étudier des possibilités de réactivation ou d'assistance en vol, une recherche sur le terrain a été entreprise.

La méthode et les premiers résultats de la phase préliminaire de cette recherche sont présentés. Au cours de cette phase, deux objectifs étaient poursuivis :
- mettre au point une méthode d'étude utilisant simultanément le monitoring physiologique et l'observation de la tâche et de l'environnement du pilote,
- rechercher les conditions favorisant l'hypovigilance, c'est-à-dire essentiellement la monotonie et la diminution de la charge de travail.

METHODE

Huit vols long-courriers ont été effectués au cours de cette phase préliminaire. Tous ces vols ont été réalisés avec des équipages composés de volontaires. Pour quatre de ces vols, on a privilégié des vols de nuit, caractérisés par des situations monotones sur des trajets Nord-Sud. Ces vols se sont déroulés sur B747 pour des rotations Paris-Libreville-Paris et Paris-Brazzaville-Paris. Les quatre autres vols sont des vols transméridiens qui ont été effectués entre Paris-Winnipeg-Paris et Paris-Cayenne-Paris, respectivement sur B747 et DC8.

Pour chacun de ces vols, deux types de mesures ont été effectuées :
- des mesures physiologiques,
- une observation de la tâche et de l'environnement.

Les mesures physiologiques suivantes ont été retenues :
- l'électro-encéphalogramme (EEG), afin d'analyser, après analyse spectrale, les variations des principaux rythmes : bêta, alpha, thêta et delta,
- l'électro-oculogramme (EOG) pour obtenir la fréquence des mouvements oculaires,
- la fréquence et la variabilité cardiaque,
- l'activité motrice du poignet (actométrie).

L'EEG et la fréquence des mouvements oculaires permettent de mesurer en continu des variations du niveau d'éveil. Elles constituent des moyens fiables de détecter des périodes de somnolence. L'EEG a été recueilli à partir d'une dérivation pariéto-occipitale droite nécessitant la pose de quatre électrodes : une électrode occipitale, une électrode pariétale et deux électrodes de terre placées au vertex. Cette dérivation permet d'étudier plus particulièrement la bande de fréquence alpha (8-12 Hz) dont les variations sont assez bien corrélées avec les fluctuations du niveau de vigilance (1,2,3).

Pour la fréquence des mouvements oculaires, deux électrodes ont été fixées : l'une sur une zone électriquement inactive, la mastoïde, l'autre à un centimètre au-dessus de l'oeil. A l'exception de cette dernière, tous les capteurs ont été collés au collodion qui assure une bonne fiabilité aux enregistrements de longue durée.

La fréquence cardiaque a été enregistrée au moyen de deux dérivations de type CM5 (creux axillaire droit, creux axillaire gauche). Nous nous intéressons ici davantage à la variabilité cardiaque dont les variations sont liées à la charge de travail mentale.

Pour la mesure de l'actométrie, un capteur de mouvements fixé par un bracelet sur le poignet droit des pilotes a été utilisé. Ce capteur comptabilise les déplacements à partir d'une détection d'accélérations. Ce paramètre permet de suivre sur des enregistrements de longues durées le déroulement des cycles activité-repos.

Ces mesures physiologiques ont été enregistrées sur deux centrales d'acquisition miniaturisées différentes, fournissant deux types de traitements :

- l'EEG, la fréquence des mouvements oculaires et la fréquence cardiaque sont enregistrés sous forme analogique sur une bande magnétique. L'enregistreur utilisé est un MEDILOG-MD4 fixé à la ceinture du sujet,
- le deuxième enregistreur est une centrale d'acquisition numérique VITALOG PMS-8 sur lequel la fréquence cardiaque et l'actométrie sont enregistrées. Ce système est également fixé à la ceinture du sujet.

Les données analogiques de l'EEG, de la fréquence des mouvements oculaires et de la fréquence cardiaque sont numérisées après relecture sur une platine OXFORD-PB4 à 60 fois la vitesse d'enregistrement. Les logiciels développés permettent de réaliser :

- une analyse spectrale de l'EEG dans la bande 0,5-30 Hz sur des périodes de 2 à 60 secondes,
- une édition des résultats sous formes graphiques, représentant l'évolution des rythmes alpha, bêta, delta et thêta au cours du vol ; cette édition peut être réalisée sous forme de puissance absolue et puissance relative pour les différentes bandes de fréquence, ou de rapport de spectres,
- une édition de la fréquence et de la durée des clignements des yeux,
- une analyse spectrale de la fréquence cardiaque dans la bande 0,001-0,5 Hz,
- une édition sous forme graphique de l'évolution du spectre particulièrement dans les bandes 0,001-0,05 Hz, 0,05-0,15 Hz et 0,2-0,5 Hz.

Parallèlement aux mesures physiologiques, une observation de la tâche et de l'environnement est effectuée. Ces observations demeurent le complément indispensable du recueil des paramètres biologiques dans la mesure où elles permettent d'éliminer de l'analyse, les segments pour lesquels l'activité physique interfère avec la tâche, mais surtout de caractériser l'environnement du pilote, son état et la tâche dans laquelle il est engagé. Cette observation est réalisée à l'aide d'une grille de codage mise au point lors d'études antérieures (9) et adaptée aux besoins particuliers de cette recherche (figure n° 1). L'environnement du pilote est défini par l'environnement opérationnel : zone de contrôle radar, surveillance radar, espace libre, ainsi que par les conditions météorologiques.

1	2	3	4 à 9 CM1, CM2, CM3		10	11	12	13
Phase de vol	Gestion Vol	Pilote	Etat	Tâche	Communication	Envi.Oper.	Météo	Evénement
0	0	0	0 Veille (Y.O)	0 Aucune	0 Silence	0	0	0 Normal
1 Pre-taxi	1 Pré-Opérat.	1 CM1 PAC Man.	1 lecture	1 Déf.route	1 Equipage	1 Contr.Radar	1 Clair, Calme	1 Anomalie
2 Taxi	2 Bef.Start CL	2 CM2 PAC Man.	2 Repos (Y.O)	2 Chgt.route	2 PNC	2 Surv.Radar	2 Clair, Turb.	2 CL/Anomalie
3 Take-off	3 Engine Start	3 CM1 PAC P.A.	3 Repos (Y.F)	3 Chgt.niveau	3 Passager	3 Espace libre	3 Nuages, Calme	3 Incident
4 Climb	4 Aft.Start CL	4 CM2 PAC P.A.	4 Pause repas	4 Evitement	4 ATC	4	4 Nuages, Turb.	4 CL/Incident
5 Cruise	5 Briefing	5	5 Pause Boisson	5 Proxi.Avion	5 ATIS	5	5 Orages	5 Panne
6 Descent	6 Check-List	6	6 Debout marche	6 Radio Com.	6 Cie.Mainten.	6	6 AP, Visi.<<	6 CL/Panne
7 Approach	7 Final CL	7	7	7 Monit.Carb.	7 Cie.Commerc.	7	7	7
8 Landing	8 Status	8	8	8 Monit.Tech.	8 Assist.Sol	8	8	8
9 Taxi aft.land	9 Autre	9	9 Autre	9 Autre	9 Autre	9	9 Autre	9 Autre

<u>Figure n° 1</u>
Grille de codage des phases de vol et des tâches de pilotage long-courrier.
Etat actuel du codage : - de l'activité des différents membres de l'équipage,
- des conditions du vol et de l'environnement.

Cette grille permet de coder les phases de vol, les procédures engagées, des événements anormaux éventuels, ainsi que la répartition des tâches entre le commandant de bord, le copilote et le mécanicien. Ces codes sont donnés pour l'ensemble de l'équipage, le type de communication engagée est également identifié pour l'ensemble de l'équipage. Ceci élimine les communications individuelles et conduit à privilégier la communication actuelle la plus importante. L'état du sujet (veille, repos ou autre) et la tâche sont par contre identifiés pour chaque membre d'équipage.

PREMIERS RESULTATS

- Observation de l'activité de l'équipage -

Une première analyse des résultats met en évidence une grande diversité des observations effectuées due à plusieurs variables :

- vol de nuit ou de jour,
- activité antérieure du pilote (repos, décalage horaire, rotations nocturnes),

- la région survolée (zone atlantique à faible trafic aérien, zone terrestre à trafic aérien faible ou important).

Cependant, certaines tendances peuvent être dégagées :
- la première concerne l'analyse des communications qui montre qu'il existe d'importantes modifications dans la nature et dans la durée des communications selon la phase de vol dans laquelle le pilote est engagé. Le silence tend à augmenter au cours du vol et devient prépondérant lors des phases de croisière (figure n° 2). Par ailleurs, les communications entre les membres de l'équipage semblent être plus importantes lors de vols de jour que lors des vols de nuit.

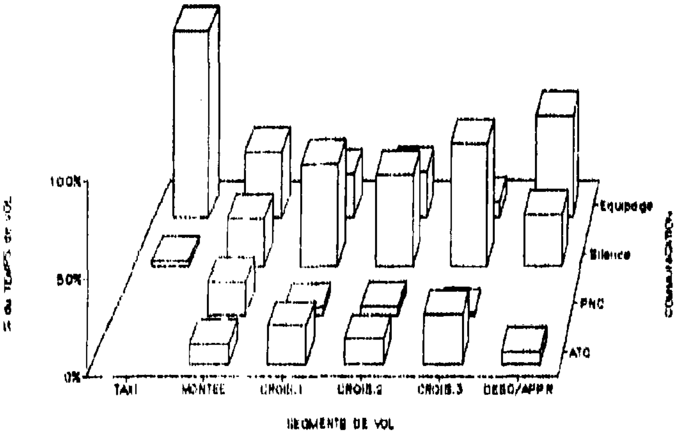


Figure n° 2
PARIS - BRAZZAVILLE, UTA, XX/11/88 - Répartition des temps de communication.

- la seconde tendance qui peut être dégagée concerne les périodes de repos yeux ouverts ou yeux fermés qui sont plus nombreuses lors des phases de vol de croisière. Parallèlement, on voit une diminution assez nette de la veille lors de ces phases, puis une augmentation lors des phases d'approche et de descente (figure n° 3).

- Paramètres physiologiques -

Afin de déterminer les variations au cours du temps de l'actométrie et de la fréquence cardiaque, les valeurs sont représentées sous forme d'histogrammes. Les valeurs sont regroupées par classe :
- *fréquence cardiaque :*
  - . entre 170 et 200 battements par minute : classes de 10 battements,
  - . entre 50 et 165 battements par minute : classes de 5 battements,
- *actométrie :*
  - . entre 100 et 200 impulsions par minute : classes de 50 impulsions,
  - . entre 50 et 100 impulsions par minute : classes de 25 impulsions,
  - . entre 10 et 50 impulsions par minute : classes de 5 impulsions,
  - . entre 0 et 10 impulsions par minute : classes de 2 impulsions.

A l'examen des tracés, on peut constater que les cycles activités-repos sont aisément identifiables sur la restitution des enregistrements d'actométrie, les périodes de repos étant caractérisées par une baisse très nette, voire une disparition complète des mouvements du poignet pendant le sommeil (figure n° 4). Il est possible de cette manière d'objectiver des privations partielles de sommeil, dont on sait par ailleurs qu'elles peuvent induire des somnolences diurnes en situation monotone. Les oscillations de la fréquence cardiaque moyenne sont observées en liaison avec des phases d'activité physique, du pilotage proprement dit, ainsi que pour les fluctuations à long terme dues aux rythmes circadiens. Cette étude des fluctuations circadiennes sera complétée, pour la suite des vols, par un recueil en continu de la température corporelle.

- Analyse spectrale des activités EEG et EOG -

Le calcul des spectres de puissance de l'EEG a été réalisé pour des séquences de 30 secondes ce qui permet de détecter des périodes d'hypovigilance de courtes durées. Les figures n° 5 et 6 montrent respectivement un spectre de puissance EEG au début d'un vol Nord-Sud de nuit et un spectre enregistré sur le même sujet 1 heure 30 après le décollage. On note une augmentation importante de la puissance dans la bande de fréquence alpha entre ces deux périodes. Cette augmentation de la puissance alpha se retrouve par périodes tout au long du vol comme le montre l'évolution des spectres au cours d'un vol de nuit (figure n° 7). Les mêmes phénomènes sont constatés lors d'un vol transméridien de jour, ce vol étant consécutif à un repos lors d'une escale durant lequel le pilote a subi une privation partielle de sommeil objectivé par l'enregistrement d'actométrie (figure n° 8). On peut noter d'importantes modifications dans la bande de fréquence alpha après quatre heures de vol.

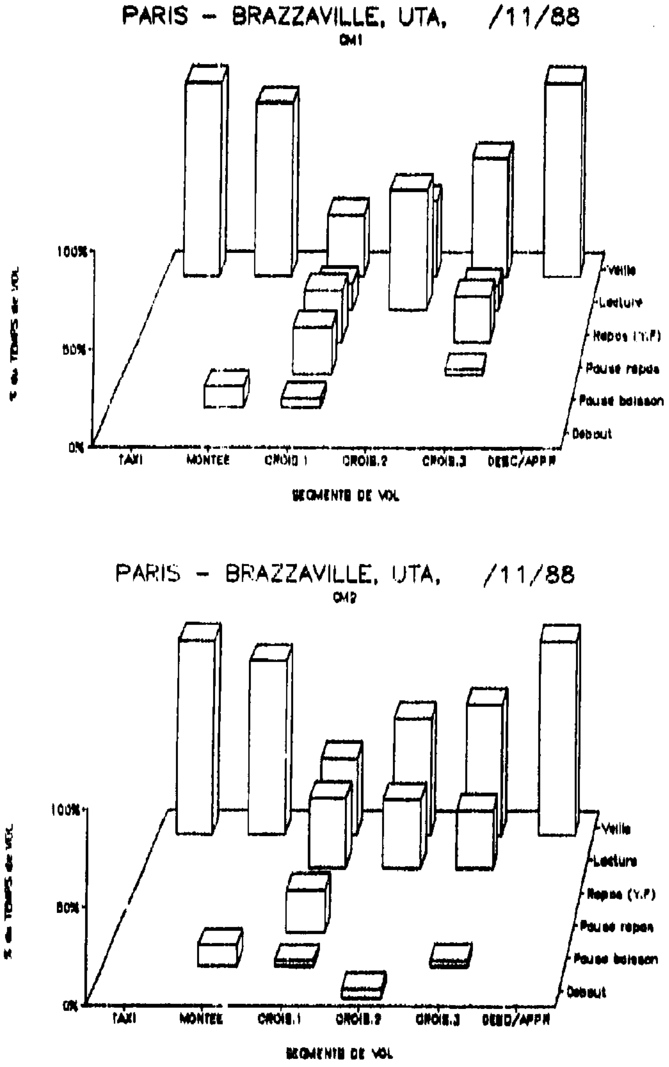
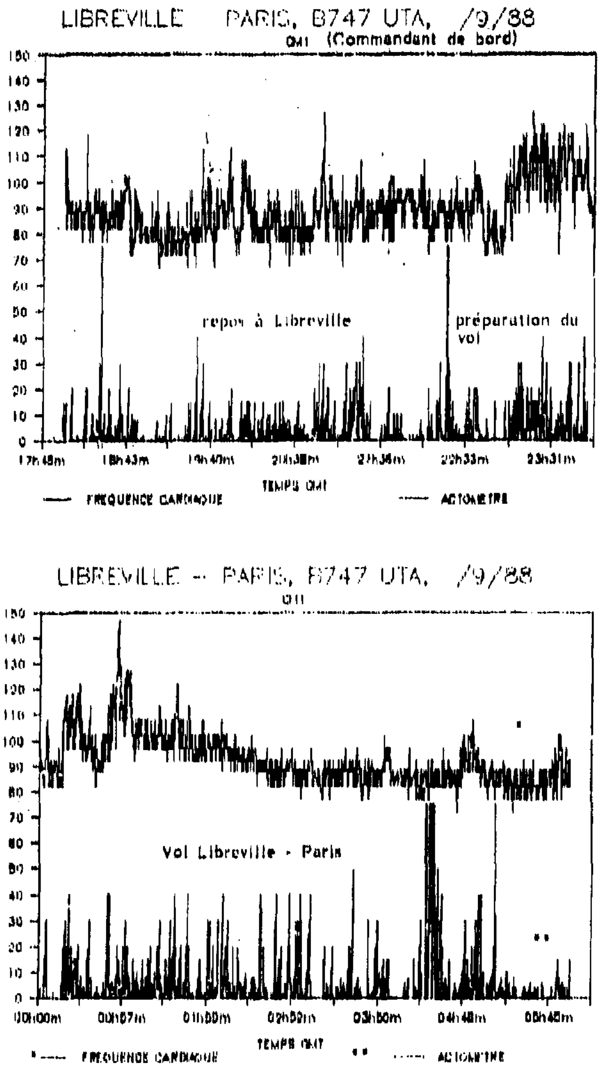


Figure n°3
Observation de l'état du commandant de bord (en haut) et du copilote (en bas), en fonction des différents segments de vol au cours d'un trajet Paris-Brazzaville.


LIBREVILLE PARIS, B747 UTA, /9/88
CM1 (Commandant de bord)

LIBREVILLE - PARIS, B747 UTA, /9/88
CM1

Figure n°4
Evolution de la fréquence cardiaque et de l'actométrie au cours d'une escale (en haut et d'un vol Libreville-Paris (en bas).

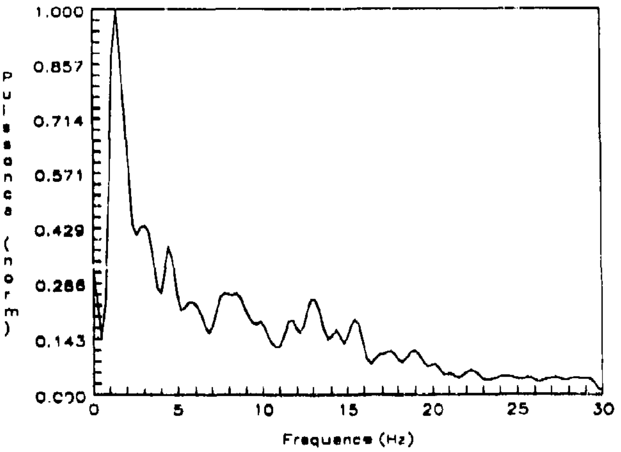


Figure n°5
Spectre de puissance de l'activité EEG pour une séquence de 30 secondes.
Extrait d'un enregistrement effectué sur le copilote d'un équipage au début d'un vol de nuit (15 minutes après le décollage).

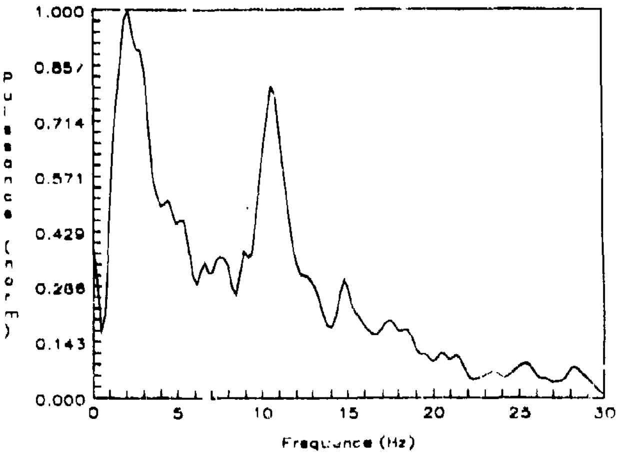


Figure n°6
Spectre de puissance de l'EEG pour le même pilote et le même vol de nuit, après 1 heure et 30 minutes de vol.
On notera l'augmentation de puissance dans la bande alpha.

L'analyse par bande de fréquence montre également pour un autre vol Nord-Sud, une augmentation de la puissance des rythmes delta, thêta et bêta 2 heures 30 après le début du vol pour le copilote (figure n° 9) et pour le mécanicien (figure n° 10). Cette augmentation de la puissance totale du spectre peut être interprétée comme une baisse de la vigilance. Il est donc intéressant de constater que cette hypovigilance intervient au même moment, pour deux membres de l'équipage. Les tracés du commandant de bord, pour ce vol, ne peuvent être présentés en raison de problèmes techniques apparus lors de l'enregistrement (importants parasites liés à une électrode en partie décollée à la suite d'un choc de la tête de ce pilote contre la paroi supérieure de la cabine).

Une baisse de la fréquence des clignements oculaires est également constatée parallèlement à des modifications de l'activité EEG, notamment lors d'augmentations du rapport alpha-delta et alpha-thêta.

En résumé, on peut formuler les remarques suivantes :
- le recueil des activités EEG et EOG peut s'effectuer de manière acceptable dans des conditions réelles de vol,
- des fluctuations de l'activité EEG peuvent être mises en évidence sur les spectres de puissance principalement pour les bandes alpha et delta,

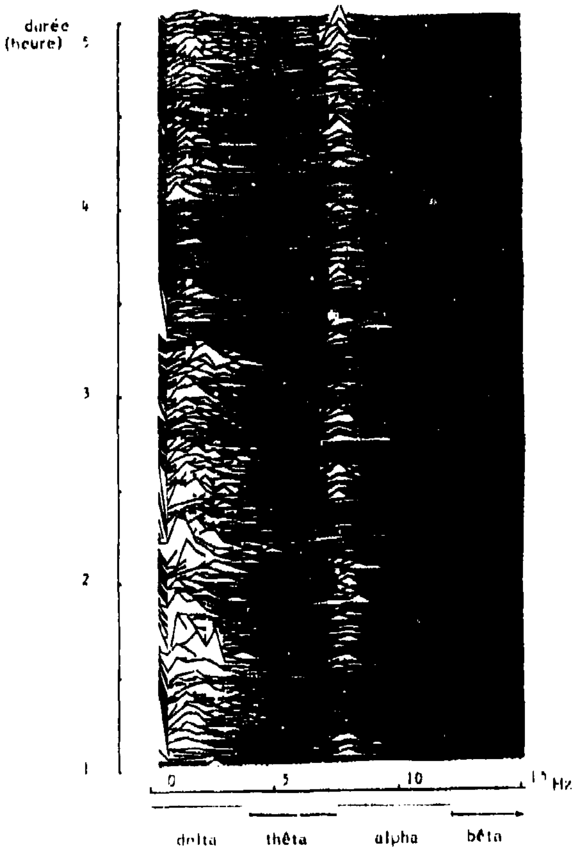


Figure n° 7
Variation du spectre EEG (bande 0-15 Hz) sur un vol de longue durée de nuit.

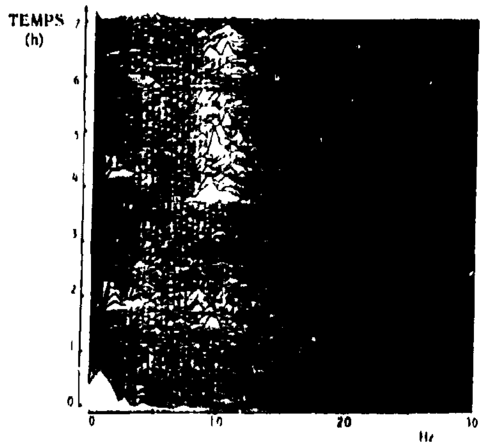


Figure n° 8
Variation du spectre EEG pour un vol de jour, après une privation partielle de sommeil lors de l'escale.

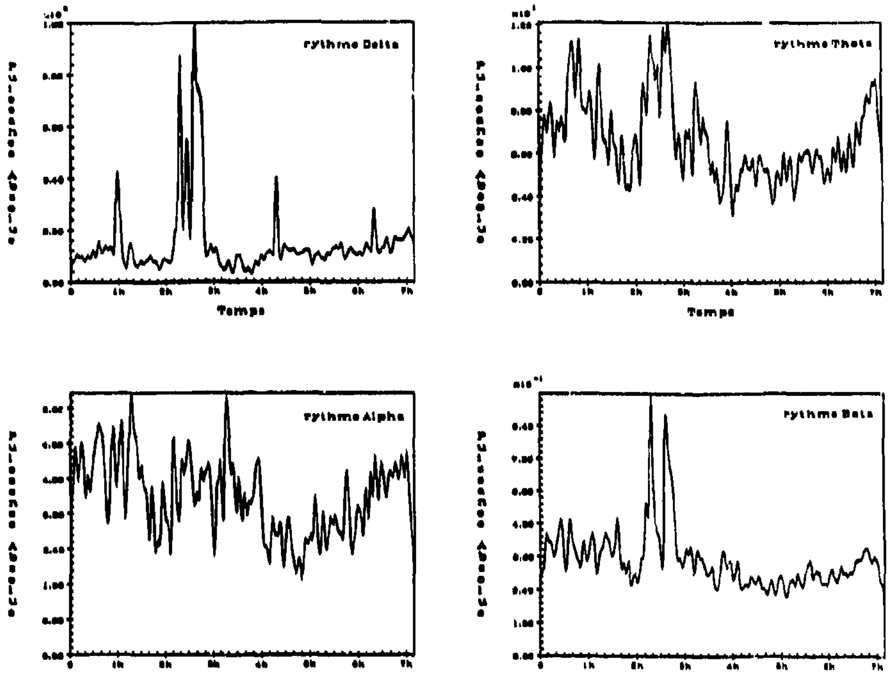


__Figure n° 9__
Exemple d'évolution des différents rythmes EEG pour un vol de jour dans le sens Nord-Sud.
Enregistrements effectués sur le copilote.

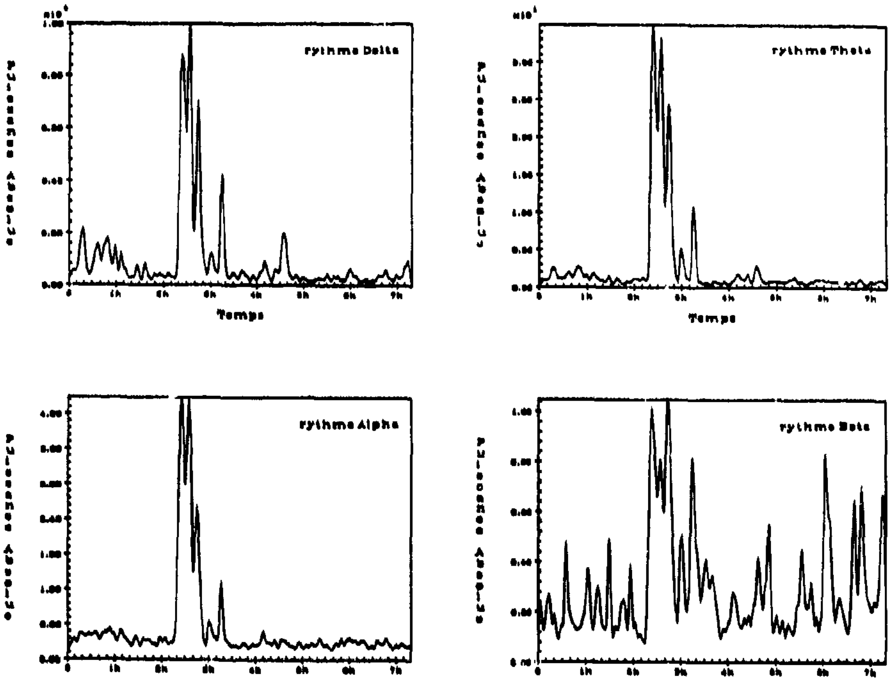


__Figure n° 10__
Enregistrements effectués sur le mécanicien.

- les augmentations très nettes des rapports alpha-thêta et alpha-delta, qui traduisent les modifications de l'activation du pilote, se retrouvent préférentiellement dans les vols de nuit et dans les vols de jour consécutifs à une privation partielle de sommeil,
- ces phases pour lesquelles la baisse de vigilance est la plus marquée, ont été identifiées principalement pour des séquences d'activité de surveillance au cours des phases de croisières.

CONCLUSIONS

Cette phase préliminaire a permis d'aborder essentiellement les problèmes de méthodes liés aux enregistrements physiologiques effectués en ambulatoire au cours de vols de longues durées. Cependant, une première analyse montre qu'il existe d'importantes variations dans les spectres d'EEG quantifié et dans la fréquence des mouvements oculaires. Des alternances de phases durant lesquelles les pilotes présentent une vigilance élevée avec des phases de somnolence ont été observées pour chaque membre de l'équipage. Les privations de sommeil au cours des escales ont des répercussions sur le comportement des pilotes. En particulier la baisse de vigilance paraît plus prononcée pour les vols qui suivent une nuit avec privation de sommeil, même si ce vol est effectué durant la journée.

La seconde étape de cette recherche, qui se déroule actuellement, porte sur 50 vols long-courriers. L'analyse des données sera centrée sur l'identification des phases d'hypovigilance, la répétitivité de ces phases, leur interaction avec les tâches et les activités des pilotes, ainsi que sur l'effet cumulé de la monotonie, du "jet-Lag" et de la privation de sommeil.

Les résultats attendus devraient permettre d'établir des recommandations relatives aux horaires et à l'organisation du travail des équipages. Par exemple, des périodes de sommeil de courte durée avec une périodicité et une durée à définir pourraient être proposées dans le but de maintenir l'efficience de chaque membre de l'équipage.

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EVALUATION OF THE PERFORMANCE CAPABILITY
OF THE AVIATOR UNDER HYPOXIC CONDITIONS
OPERATIONAL EXPERIENCE

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ABSTRACT

Performance capacity under hypoxia conditions was determined in 48 subjects exposed to a simulated altitude of 25,000 feet (7,620 mts.). The method was a modified Toulouse-Pieron Test (TTM) and a Digit Span Test (DST), completed at 3 conditions: Ground Level (GL), FL 250 and Placebo (PL). Maximum hypoxia time was 4 minutes and it was measured every 30 sec. We obtain the Direct Partial Score (DPS) 8 times through the 4 min., and the Direct Total Score (DTS) by the Tolouse application formula. Significant decrements in test performance were found by comparing GL - FL 250 and FL 250 - PL in pairs at .001 confidence level after point 90 sec. time for DPS. We got similar results for DTS. For DTS, the comparative analysis of the average values were also significant. The application of the TTM is considered as useful, simple and profitable in the evaluation of Attention Capacity of the aviator under hypoxia conditions. The "Incapacitation Curve" is a term which expresses, in a quantitative and cronological way, the psychomotor performance. Both, the TTM and DTS, are between each other complementary tools in the evaluation of the psychomotor pilot efficiency.

INTRODUCTION

The quantitative evaluation of the intellectual and psychomotor performance of the flyer is a valuable data, in the determination of the effects of hypoxia (1,2).

Although this information has been useful, the results have often been contradictory (5,7,8).

Sensitive methods of measuring system error, using qualified pilots in both real and aircraft simulators, have been developed (2,3), but very little data is available on the critical time, referred to as the time of Useful Function, as a point or decay along the progressive performance deterioration, which reflects the pilot's intellectual estimation under hypoxia conditions.

O'Connor (6) described the Performance Rate as the ratio of task units completed in a unit time under hypoxic conditions over task unit time completed per unit time under non-hypoxic conditions. The result, an index value, is a metric, which would permit comparisons of different tasks sensitive to hypoxic conditions.

The reaction capacity against any imposed task, is a complex of factors, which included reasoning, psychomotor and a visual factor. The reasoning factor aims to discover rules or principles in order to arrive at a solution. To help such a factor perceptual and psychomotor supportis necessary.

The aviator must be alert thoughout the flight, in order to prevent any contingency, accident or incident. He should recognise any stimuli from the surrounding space in order to make, control and direct a movement (final integration of an elaborated answer), according to the corresponding stimuli. More recently Israeli and al. (4) in a new approach to the TUC evaluation at 25,000 feet, studied the loss of minimal attentive capabilities, manifested by the inability to add two-digit numbers correctly.

The Toulouse-Pieron Test (TTM) measured the sustained attention fatigue resistance, psychomotor factors and personality. Fatigue resistance is defined as the capacity to perform a repetitive and routine task with an acceptable output.

It is a useful test in order to evaluate cognitive and psychomotor aspects in a variety of tasks which, demands constant attention and fatigue resistance.

The test is easy to carry out and free of any external incluence. It has an important saturation point in topological factors, active perception and static visual factors.

The Digit Span Test measures the Attention Capacity and Distraction Resistance of the subject. The task is intellectual and it does not offer any emotional link. The test could be an indicator of the pilot ability or intellectual skill under hypoxia condition.

This paper reports our experience, in a two complementary test which allow simple and objective evaluation of the "Performance Capacity" of the aviator under hypoxic conditions.

METHODS

A standard altitude chamber (ETC APTF 10M) was used, the camber can accomodate 10 trainees in the main compartment and two in the R/D compartment plus 2 + 1 instructor. An Oxigen system is supplied to each individual throughout an Oxigen automatic pressure-demand regulator. Fourty-eight healthy aircrew members were chosen with an average age of 23.73 + 3.63, weight 72,21 Kg + 8.02 and a height of 175.67 cm + 7.05. The study was carried out at a simulated altitude of 25,000 ft. (7,620 mts.). This altitude was chosen taking into account the pressurization profile of most of the fighters (22,000-25,000 ft.), and the minimum altitude in which Decompression Sickness starts to be significant.

The study was carried out under three different conditions:

1) At Ground Level (altitude = 602 mts.) (GL).

2) At 25,000 ft. (7,620 mts.) (simulated altitude in a decompression chamber). (FL 250).

3) Placebo or Control Flight (PL) at 7,620 mts. (FL 250, not real), the real simulated altitude reached was 1,500 mts. The time and procedures of this flight were similar to the FL 250 profile.

The Placebo flight established which emotional and stress factors are linked to the experimental situation. These factors could be evaluated separately from the stress factors strictly associated with the FL 250 flight.

A denitrogenation period of 30 min. followed an ear and sinus check at 5,000 ft (1,524 mts.). Ascent and descent rates were 4,500 ft/min. Oxigen masks were removed and the Oxigen supply switched off before starting both tests in conditions FL 250 and Placebo. The evaluation was made by the application of the Toulouse-Pieron Test modified for this purpose, and, in a two-minute interval, the Digit Span Test.

The Toulouse-Pieron modified test is one page form that includes blocks of 400 figures in pairs, one par for each condition. The task consisted in locating and marking among the elements of each line, the figures equal to the pattern. Each line has 10 figures to mark, and their distribution is randomized. The task should be done in the shortest time possible.

We have considered the total number of lines completed at a time limit of four minutes and also the proportional lines completed every 30 seconds.

Scores are obtained, taking into consideration the proportional periods marked by the trainee every 30 seconds, called direct Partial Score (DPS) and the total number of lines completed in 4 minutes, called Direct Total Score (DTS).

To get the Scores we used the Toulouse-Pieron Formula:

DPS = Possible successes scores - (errors + 2x omissions) every 30 sec.
DTS = Possible successes scores - (errors + 2x omissions) in 4 min.

The Digit Span Test includes three blocks of numbers, one for each condition and divided in two parts. The first one consists of repeating series of numbers, announced by the instructor. The second one is in an invers order. The test started with a serial of three digit numbers, the number of digits is increased in each number line, until a maximum of nine. The test is finished when the trainee fails twice. The second part proceeds in the same way until a maximum of eight.

We obtain two tipes of final scores:

1) Direct Score : X + X'

2) Tipical Score : Direct application of a Table.

Statistics were made by the SPSS PC. We studied the intrasubject varianza analyis, considering the condition Altitude and Time. We made the comparative analysis of the mean scores in each condition, and the comparative analysis of the mean partial scores in successive pairs.

RESULTS

TOULOUSE-PIERON MODIFIED TEST:

We have seen how Time and Altitude have a global efect on each subject and is significant in relation to the Altitude (.001 Confidence Level), to the Time (.001) and also to the Altitude-Time relationship (.001).

The comparative analysis of averages at each condition shows a significant decrement in test performance by comparing in pairs, Ground Level and FL 250, at .001 confidence level after point 90 sec. for Directo Partial Scores. We found significant differences by comparing in pairs GL and PL, only at the begining of the test, for DPS (See Figure 1 and 2).

For DTS we found similar results in GL-FL250 and FL250-PL at .001 confidence level, and the condition FL250 presented the lowest result. The comparative analysis of the average values in pairs of succesive scores in each condition will make it possible to identify the evolutionary course of the DPS throughout the time. It means that we can observe the point at which a significant change occurs in the score pattern.

Figure 3 shows the evolution of the scores in each condition. We see how at FL 250 there was a constant decrease of the average values in relation to the time, after point 60 sec.

We observed how at GL scores at 30 sec. and 60 sec., they are lower than the following ones. Something similar it happens at FL250 and Placebo. At the end of the Placebo condition we found a significant score decrease.

DIGIT SPAN TEST:

The comparative analysis of the mean average values in relation to the three conditions studied were significant for Direct Scores (See Figure 4).

- GL-FL250 : minor than .001
- GL-Placebo : minor than .01
- FL250-Placebo : minor than .001

The Typical Scores show statistical differences, and results are much more similar to Direct Scores.

- GL-FL250 : minor than .01
- GL-Placebo : minor than .05
- FL250-Placebo : minor than .001

DISCUSSION

The analysis of the time factor under the GL condition, shows a high confidence level. It is necessary to use the evolution of the scores through the whole Toulouse-Pieron test, in order to evaluate the real significance of such results. There is no differences after 90sec. time. We should attribute this to the normal learning effect at the beginning of the test.

The evolution of the time factor under condition FL250 shows lower sucessive scores, this is more manifested after 180 sec. It could be said, this evolution describes what we could call the "Incapacitation Curve."

O'Connor (6) found similar results but the method he employed is much more elaborated and performed by one trainee.

Israeli et al (4) described the loss of minimal attentive capabilities by adding pairs of two digit numbers at random. They also found a drop of probability after 180 sec. and it is very evident at 240 sec.

We have considored a time limiting factor of 4 min. which means a drop of 40% in the score evaluation, in relation to GL and PL., determining factor to assume that performance capabilities are impaired.

The analysis of the Placebo condition shows a similar Pattern to GL conditions, but scores at 210 and 240 sec. are lower than we found after a period of 90 sec. It could be due to distraction and fatigue factors, something we should take into consideration after a prolonged time inside the Altitude Chamber.

The lack of global statistical significant difference between the GL and PL pattern exclude any psychological or stress factors linked to the experimental situation.

In relation to the Digit Span Test we observe that its evaluation is exclusively linked to the final score. There is no time limit, but the test was finished in less than three minutes. We found significant differences in the comparative analysis of each condition. The fact of the "nul hypothesis" does not occur in the comparison of GL-Placebo, which means an emotional and probably fatigue factor at the end of the test.

According to Zimmerman (9) this test is a good indicator of the audio-verbal attention capacity and skill to face a simple task.

We understand that the modified Toulouse-Pieron test and Digit Span test is a useful simple and complementary tool in the evaluation of the "Attention Capacity" of the aviator under hypoxia conditions and measures in a quantitative, global ans cronological way the psychomotor pilots efficiency.

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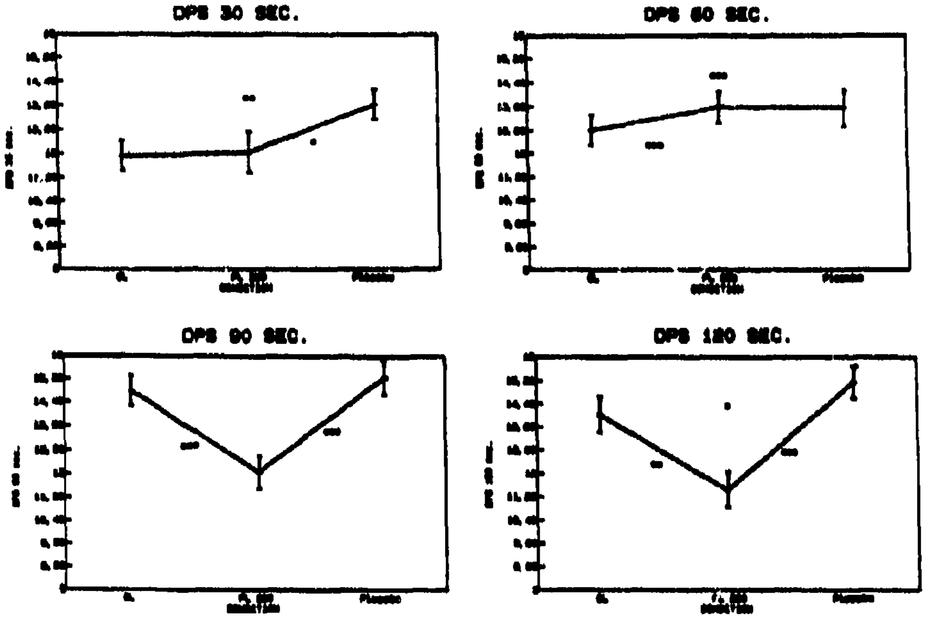
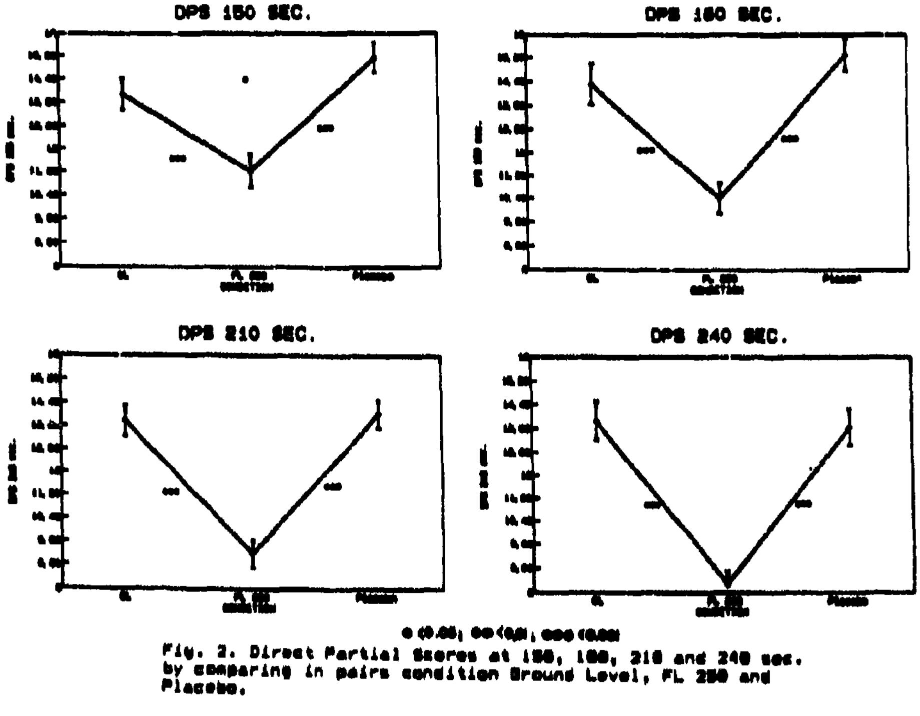


* (0.05), ** (0.01), *** (0.001)

Fig. 1. Direct Partial Scores at 30, 60, 90 and 120 sec. by comparing in pairs, conditions Ground Level, FL 250 and Placebo.



* (0.05), ** (0.01), *** (0.001)

Fig. 2. Direct Partial Scores at 150, 180, 210 and 240 sec. by comparing in pairs condition Ground Level, FL 250 and Placebo.

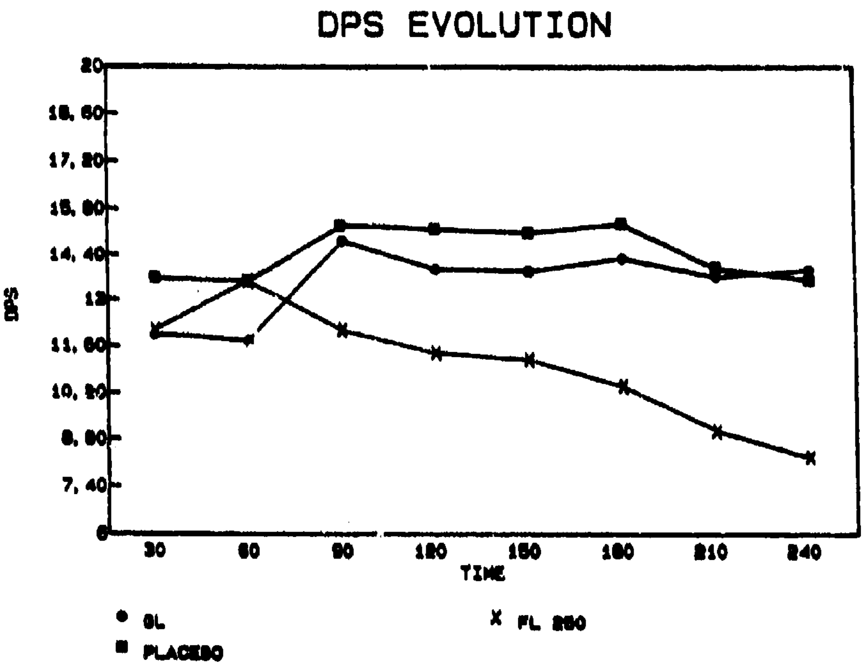


Fig. 3. Evolution of the scores in each condition.

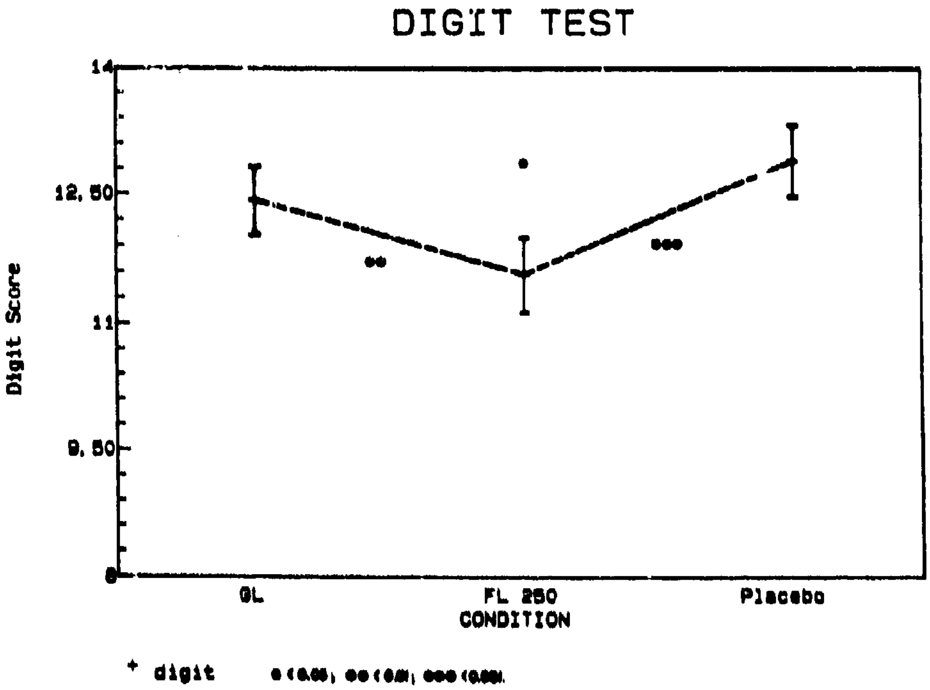


Fig. 4. Digit Span Test Scores.

EFFECTS OF SHORT-TERM WEIGHTLESSNESS ON ROLL CIRCULARVECTION

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SUMMARY

Roll circularvection is an illusion of self-rotation about the fore-aft axis experienced when a stationary subject is exposed to a visual field rotating in the frontal plane. In these experiments, subjects have been asked to estimate the strength of this phenomenon while undergoing visual stimulation in the upright and supine positions, and during parabolic aircraft flight. The results indicate that the steady roll component of vection is not affected by the magnitude or direction of the gravity vector. The unpredictable and sudden loss of this compelling illusion could contribute to serious episodes of pilot disorientation.

INTRODUCTION

The work described in this paper was conducted in support of an experiment to be carried out during the first International Microgravity Laboratory mission on Shuttle. That experiment will measure the relative contributions of vision and vestibular sensory information to spatial orientation, and how these contributions change during prolonged weightlessness. The present article will not deal with the neurophysiology of space flight, but will describe the phenomenon being measured (circularvection about the roll axis), our studies of it, and how it could contribute to spatial disorientation in pilots.

Circularvection is a compelling vestibular-like sensation of self-rotation experienced when a stationary subject is exposed to a rotating visual environment (1,3). Roll circularvection is experienced when the visual field rotates in the frontal plane. Typically, if the subject is upright, a paradoxical illusion of steady roll rotation combined with static roll tilt results. If the subject is supine, and the field rotates about the gravity vector, only rotation is perceived and no tilt.

As a purely subjective phenomenon, roll circularvection has been difficult to quantify, even under laboratory conditions. In more operational environments, those data which have been collected have tended to be quite variable, forcing the use of measures such as latency of onset, which may or may not correlate with strength of vection (6,7).

We have attempted to develop more reproducible methods of measuring vection for the space experiments. In the process, we were surprised to find that vection was most easily obtained and quantified when the rotating stimulus did not occupy all of the subject's peripheral visual field (4), and that the steady roll component did not appear to be affected by the magnitude or direction of the gravity vector.

METHODS

The experiments were conducted in 2 stages. Initially, circularvection was measured in 20 subjects who were tested in the upright and supine positions. The same experiment was then carried out on 5 subjects (one of whom had been in the first group), comparing the response obtained during parabolic flight to that measured in the upright position while the aircraft was stationary on the ground.

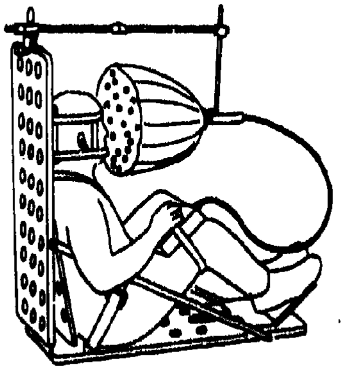

FIGURE 1. Subject restrained in seat with the visual stimulator and box with circularvection-indicating crank in position.

During all experiments, the subject was tightly restrained in a special seat by means of a 4-point harness and head straps (Fig. 1). The feet were also secured to the seat base for tests in the supine position. A dome-shaped visual stimulator was positioned with its rim 75 mm ahead of the subject's cornea, so that it occupied about 140° of his visual field. This provided the subject with a limited view of the outside world beyond the rim. The inner surface of the dome was constructed of white fabric printed with many randomly-placed coloured dots (19 mm diameter). The visual stimulus consisted of continuous rotation in either direction at 30, 45 or 60°/sec. This continued for 40 sec in the first set of tests, and 18-20 sec in the second, the latter being set by the duration of each zero gravity parabola. Dome velocity and direction, and subject orientation, were randomised in the first experiment. This was not feasible in the aircraft, so a fixed sequence of tests was repeated 3 times.

The subject was instructed to stare at infinity (not at the much closer surface of the dome), don't blink and don't move the eyes. When the dome was rotated, and vection began, the outside world as seen with extreme peripheral vision only appeared to rotate with the subject in the direction opposite to the dome. In fact, any other object fixed in the field of view would have behaved the same way (1). The subject was instructed to rotate a crank attached to a 360° potentiometer, matching the speed of rotation of the crank to the apparent speed of rotation of the outside world.

To measure the response in the supine position, the entire apparatus and subject were tilted backwards by 90°. While tactile cues and the view of the outside world must be different in the two positions, at least the subjects were always fully relaxed and in the same posture. The parabolic flight experiments were carried out in the NASA KC-135. This is a large, transport category aircraft which provides 40 periods of weightlessness on a typical flight, each lasting up to 25 sec. Generally, 18 to 20 sec of that time are usable for testing. The seat was bolted to the floor of the aircraft during these maneuvers. Control experiments were conducted under the same conditions, but with the aircraft parked on the ground.

During the first set of experiments, dome and crank angular position were recorded directly by computer, which also provided cues for beginning and ending the test stimulus. During the flight experiments, dome and crank position were recorded continuously on an FM tape recorder, and played back into the computer at a later date. The stimulator was turned on by the operator as soon as steady weightlessness was achieved, and turned off just prior to pull-up.

RESULTS

All subjects in both sets of experiments experienced strong roll circularvection which had a very sudden onset. However, as reported previously (6), vection is not a particularly stable phenomenon, having a variable latency, variable strength, and occasional "drop-outs" during which it suddenly disappears for a period of time. The latter could be provoked by blinking the eyes, changing the direction of gaze, or moving the limbs or body. Distractions such as unexpected movement in the subject's peripheral visual field, or a sudden noise, had the same effect.

Figure 2 is an example of the results obtained when the subject was upright and the dome was rotating at 30°/sec in the counter-clockwise direction. Cumulative angular position of the dome (lower curve) and the crank (upper curve) have been plotted as a function of time. The dome completed approximately 3.3 revolutions during this test. An example of a drop-out is seen between 16 and 23 sec.

To begin the analysis, up to 5 segments of 5 sec duration were defined during which vection was reasonably stable. Vection strength was determined in each of those segments by fitting linear regression lines to the dome and crank data and comparing the slopes. Saturated (100%) vection would indicate that the crank was being turned at the same rate as the dome. If multiple estimates of percent saturation of vection were obtained from a single record (as in Fig. 2), they were averaged. Latency of onset of vection was determined separately using expanded and differentiated plots.

Figure 3 summarises the results of the first set of experiments, averaged across all 20 subjects. The latency of onset of vection has been plotted above, and the percent saturation of vection (strength of vection) below, both as a function of dome rotation speed. Results with the subject upright have been plotted on the left, and those with the subject in the supine position on the right. The results of clockwise and counter-clockwise rotation have been plotted separately. The error bars represent one standard error of the mean. The dashed lines have been added to facilitate comparisons between graphs.

Neither the latency of onset of vection, nor its strength, was affected by the direction of dome rotation. Onset latency was also independent of stimulus angular velocity. Vection strength, however, appeared to fall off at the higher rotation rates, possibly reflecting saturation occurring at those angular velocities (2). In most cases, indicated vection magnitude exceeded the stimulus angular velocity, as indicated by % saturation greater that 100. This may be a systematic overestimation by the subjects, perhaps related to the apparent counter-rotation of dome and peripheral field. It may also reflect the application of size-distance scaling to rotary motion, in which case a

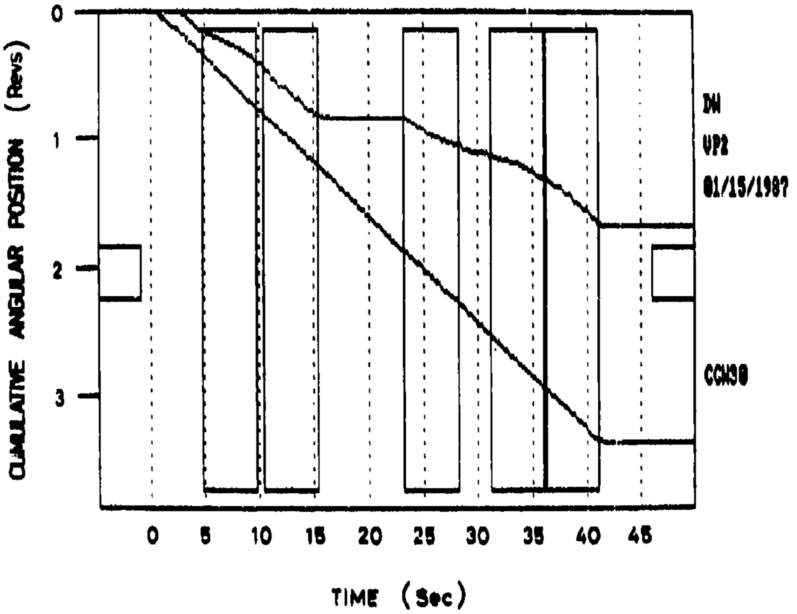

FIGURE 2. Computer-generated plots of cumulative angular position of dome (lower curve) and crank (upper curve) as a function of time. Vection strength was calculated using the segments of the curves within each rectangular box.

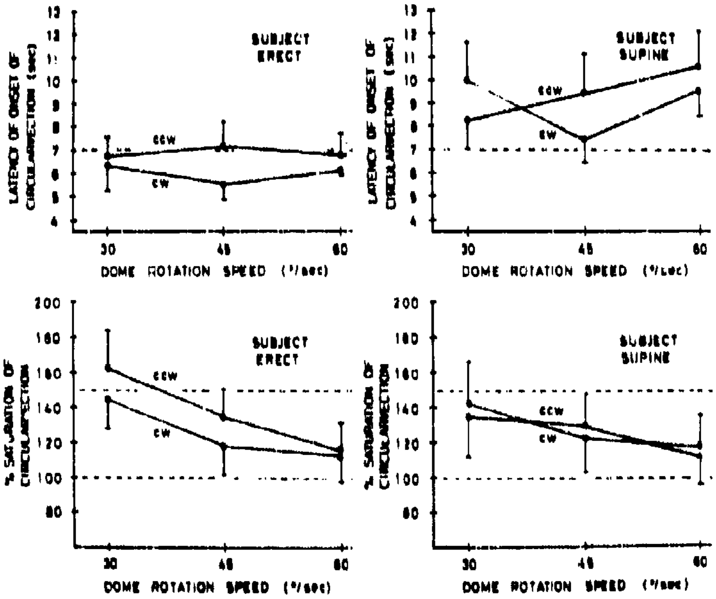

FIGURE 3. Vection onset latency and strength comparing between the upright and supine positions.

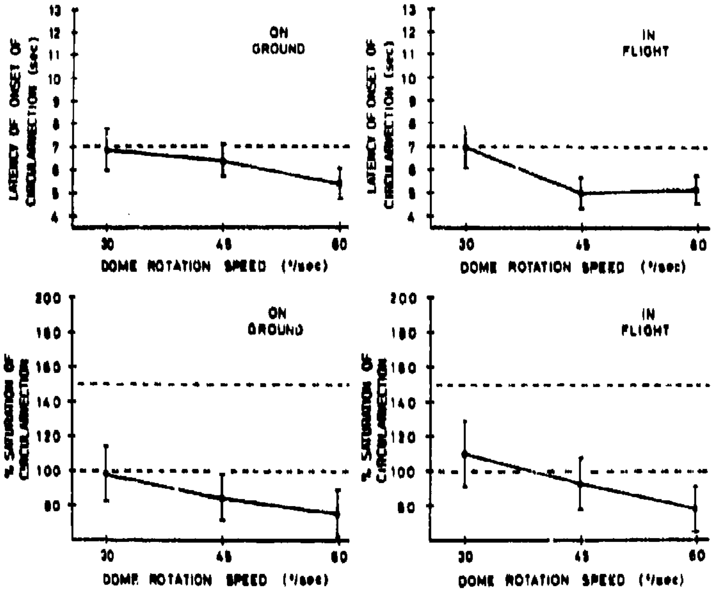

FIGURE 4. Vection onset latency and strength, comparing between one g (on the ground) and weightlessness (in flight).

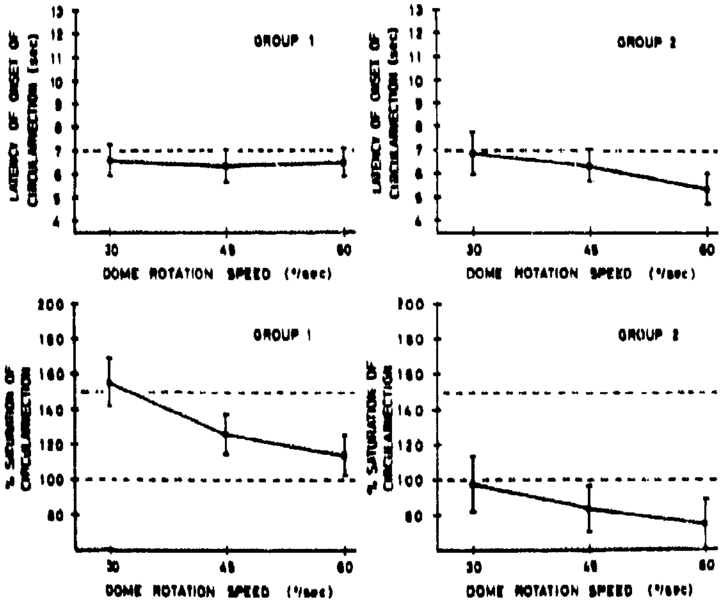

FIGURE 5. Vection onset latency and strength, comparing between group 1 and group 2 subjects, all tested in the upright position on the ground.

near object viewed while focusing at a distance would appear to move (rotate) more rapidly (5). Whatever the explanation, it indicates the great strength of the illusion. Vection onset latency was both longer and more variable when the subject was supine. However, the strength of vection was not affected by this change of subject orientation.

The demonstration that the feeling of steady rotation was not dependent on the orientation of the subject relative to the gravity vector was unexpected. However, since the vestibular labyrinth can detect linear accelerations in any direction, perhaps the presence of gravity is more significant that its direction. Therefore, the experiment was repeated in a second group of subjects, comparing roll circularvection experienced on the ground with that generated during short-term weightlessness.

Figure 4 presents the results of this second set of experiments, averaged across the 5 subjects. As before, latency results have been plotted above, and vection strength below. Control results have been shown on the left, and those obtained in weightlessness on the right. The results of clockwise and counter-clockwise stimulation have been combined here, since the previous experiments demonstrated that direction of rotation was irrelevant. The data presented in Fig. 4 do not show significant differences between the steady rotation component of roll circularvection measured in weightlessness, and on the ground. Within the limits of these experiments, the phenomenon appears to be quite independent of the linear acceleration environment.

There were some differences between the two groups of subjects, however. Figure 5 compares the control responses of the first group (on the left) with those of the second group (on the right). The results of clockwise and counter-clockwise stimulation have now been combined for group 1. While latency of onset of circularvection was identical in the two experiments, the strength of circularvection was not, averaging about 35% less when measured in group 2. This is probably a physiological difference, as the experimental equipment, procedures and methods of analysis were identical, and the one subject who was part of both groups produced closely similar results in both tests. While it is difficult to identify a precise cause retrospectively, it may be important that the average age of group 1 was 23.6 years (S.E. of mean 1.5) and that of group 2 was 45.6 years (S.E. of mean 3.5).

DISCUSSION AND CONCLUSIONS

Roll circularvection, as studied in these and other experiments, is a very compelling yet very labile phenomenon, which has a very sudden onset, and an equally sudden and unpredictable end. The drop-out of vection can be triggered by a wide variety of internal and external distractions. Vection tends to be strongest when some, but not too many, fixed objects remain in the visual field (1). The steady roll component of vection is not affected by the magnitude or direction of the gravity vector. Finally, the ability to develop vection may decline with age.

There are some apparent contradictions, however. For example, the present experiments have demonstrated increased latency of onset of vection while subjects were in the supine position, whereas those of Young (6) have suggested the opposite. The onset of vection can be delayed by many factors, and our subjects were definitely less comfortable in the supine position. In contrast, Young's subjects were lying passively on a foam mattress while supine, but actively supporting themselves when tested in the upright position.

It is also evident that latency and strength of circularvection do not correlate well. The increased vection onset latency seen in our first group of subjects when tested in the supine position was not accompanied by a change in vection strength. On the other hand, while there was no difference in latency when both of our groups of subjects underwent control tests, vection strength was significantly less in the second group. It seems clear that latency, and strength, of circularvection are influenced by quite different factors, and of the two measures, vection strength may be the more revealing.

How do these findings relate to the flight environment? Consider the situation of a pilot spinning a high-performance aircraft, in a steep nose-down position. At some point he begins to stare at the rapidly rotating ground. He would have a variety of fixed objects in his visual field, such as his helmet, the instrument panel, parts of his canopy, and so on. Within seconds, he could develop vection, and actually "see" himself and his aircraft rotating (as well as "feel" it in a vestibular sense). This would happen regardless of aircraft attitude, and since he would probably be relatively young, the vection would be particularly strong. Eventually, he would generate a control movement to initiate recovery, or shift his gaze to his instruments, thus inadvertently producing a distraction. This could suddenly stop the vection, and the aircraft would be "seen" and "felt" to stop rotating. These powerful (but false) sensations could lead the pilot to believe that the spin has ended, and he can return to straight and level flight. If the aircraft is low, continuing to descend rapidly, and the pilot's control inputs are now aggravating the continuing spin, a serious accident becomes a very real possibility.

ACKNOWLEDGEMENTS

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MAINTAINING SPATIAL ORIENTATION AWARENESS

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SUMMARY

We believe that training paradigms to vividly demonstrate to pilots the need and the way to maintain spatial orientation awareness during formation flight will reduce the incidence of these very costly mishaps. Several training paradigms are under development using the Dynasim, a cockpit mounted on a short-arm centrifuge. The pilot controls both pitch and roll axes of the Dynasim cockpit to maintain the position on a "wing aircraft" projected onto a visual surround. Pilot's attention is intermittently distracted from the lead aircraft and from attitude display(s) by simultaneous performance of other cockpit tasks. The orientation experienced by pilots is controlled by varying information in the visual surround and in the onboard instruments (including a Malcolm Horizon) and by controlling the direction of the gravitoinertial field of the short-arm centrifuge.

A second stage of our research will investigate new concepts in displays to improve pilot orientation awareness. The inevitable distraction of visual attention, which accompanies emergency situations, engenders consideration of peripheral vision and nonvisual channels to convey aircraft attitude and target information and maintain spatial orientation awareness.

INTRODUCTION

When man first entered the aeronautical environment, he encountered the challenge of "cloud flying" frequently emerging inverted, often with disastrous results. With Sperry's introduction of the gyro-stabilised artificial horizon, it was believed that pilots trained in instrument or "blind" flying would be immune to aircraft attitude disorientation. The mishaps continued despite efforts by human factor engineers to redesign instrument configuration and displays that permitted the pilot to visually interpret aircraft orientation with improved accuracy and rapidity, and despite development of regimented training syllabi including the use of Link trainers. The orientation information processing demands placed on the pilot by the introduction of faster more agile aircraft including aerobatic helicopters, and ever more demanding mission requirements including nap of the earth, night and all-weather environments will only increase the likelihood of orientation error mishaps.

Numerous surveys (1-3) spanning the past 30 years and all branches of the United States Armed Forces indicate 4-10% of Class A mishaps (500,000 dollars damage or loss of life) and 10 to 20% of fatal mishaps were a direct result of inadequate spatial awareness.

Based on a review of disorientation training practices utilised in NATO countries, a 1974 AGARD working group made specific recommendations directed towards improving ground training, training in flight, and research and development programs (4). For ground training, it was suggested a device with rotational freedom in the yaw axis alone would be adequate. The panel felt that demonstrators with yaw and pitch capabilities would not be cost effective at that time. Shortly thereafter, the Royal Air Force Institute of Aviation Medicine developed a rotational disorientation demonstrator that was accepted with such enthusiasm that a second device was brought on-line to permit all student pilots the opportunity to receive disorientation training. The U.S. Navy, which developed the 10 place Multiple Station Disorientation Device (MSDD) to provide disorientation familiarisation training to student pilots and flight officers, has now extended instruction to include all aircrew. A recurrent training schedule ensures most experienced pilots are routinely reminded of the hazards of disorientation.

Although both devices are excellent demonstrators capable of generating a variety of compelling spatial orientation illusions, they do not demonstrate to the pilot his degradation in performance or reduced ability to maintain control of an aircraft during situations in which spatial disorientation is experienced. Disorientation trainers with the pilot directly inserted into the control loop permit the pilot to experience the correlation between his flight inputs and the sensory feedback from motion and visual cues, in addition to the possibility of developing strategies to cope with aircraft control under the adverse conditions of spatial disorientation.

In the past, sensory motor research was not only split into sensory and motor divisions, but even the individual sensory systems were examined separately without concern for interaction. Hans-Lukas Teuber (5) indicated the fallacy of such dissection when he so aptly expressed, ". . . . Our brain needs to process the sensory input and extract its relevant features, but it also must compensate continuously for its own motor output and take the anticipated consequences of its own future actions into account. The unity and stability of our perceptions might therefore be more understandable if we were to trace the information flow in the central nervous system not only in traditional fashion, from sensory to motor regions, but in the reverse direction as well, so that intended and potential movements are seen to enter into the structure of our perceptions." Our perceptions of motion and hence spatial orientation are strongly influenced by the "feed forward" awareness of permitted degrees of freedom of motion and expectations (reafference) when we initiate motor programs to control motion. The active control of our positioning in space through direct machine feedback may thus produce a markedly different perception than that experienced by a passive observer receiving the identical physical stimulus. For these reasons and also in pursuit of strategies and techniques to overcome disorientation, we favor development of man-in-the-loop disorientation trainers to supplement current training regimes.

The opinion of many pilots and engineers involved in the development and acceptance of training devices that the replication of as many aspects of motion and realism as possible will lead to more efficient training has led to the production of motion-based trainers possessing roll, pitch, and yaw pilot-controlled motions in addition to planetary motion to produce mild accelerative forces up to 2.5 G. Despite the added realism, such devices have not yet been proven to offer more effective training. Manufacturers suggest (6,7) that trainers responding to pilot input will produce quantitative change in aircrew behavior postulating that simulator performance will improve with repeated exposure to disorientating stimuli and that this learning is transferable to aircraft. In view of well-known differences in feedback from motion-control actions in flight and in simulators, we have strong reservations about the transferability of behavior change if rigorous man-in-the-loop orientation training is instituted. We are optimistic about enhanced teaching impact when seasoned pilots actively experience loss of aircraft control, accompanied by training on strategies to maintain control. Thus, we are sanguine about the development and close examination of closed-loop motion platforms.

The United States Air Force has expressed an interest in obtaining several of these new generation spatial orientation trainers to minimize disorientation mishaps through education and training. The United States Navy is considering a multi-axis training centrifuge for dual utility in G-tolerance and spatial orientation training. In either situation, because it appears that the multiaxis trainers with limited G capability will soon be in our inventory, there is a requisite for training paradigms to match the expanded capabilities of these devices.

The new generation spatial orientation trainers have design limitations that are constantly being improved or upgraded. Unlimited roll, pitch, and yaw capabilities require gimbals, which in turn necessitate visual displays within the capsule in lieu of a gimbal-cluttered 360° visual surround system. The electronic visual displays are presently restricted to a 120° horizontal field of view with the anticipation of an expanded field of view in the near future. Helmet-mounted displays may eventually permit the full surround design desired for simulation of air combat maneuvering. At present, paradigms have not been developed that permit large excursion of head movements due to limitations of available visual displays.

The AGARD working group recommendations (4) for in-flight training included "pilot recovery from unusual attitudes in the presence of disorientation and other stresses." A further recommendation was to increase the realism of airborne instrument training by including external visual-search tasks. It is now possible to include these flight training recommendations into the new generation ground-based simulators under highly controlled reproducible conditions of vision, motion, and workload stress -- albeit cross-coupled (angular Coriolis) effects remain an unwanted intrusion.

Procedures and Initial Observations

Our research approach is essentially a two-stage program. First, we will develop several man-in-the-loop scenarios for spatial orientation training dealing with disorientation flight conditions we believe to be most frequently encountered and/or most dangerous. Second, we will use the man-in-the-loop scenarios developed in stage one to evaluate the effectiveness of new information channels in maintaining veridical spatial orientation awareness.

The facility designated as Dynasim was developed to augment existing NAMRL facilities for research on spatial awareness. Dynasim (8) consists of three main components: a motion system, a visual surround for presentation of earth-fixed or moving targets, and a computer system. The motion system is a short-arm centrifuge that provides yaw-axis rotation of an off-center cockpit housed in an aircraft-like fuselage that is capable of motion about its own pitch and roll axes. The computer system provides capability for presenting a variety of visual displays on two scopes (Cathrode Ray Tubes) in the cockpit instrument panel. Currently available scope displays include an Attitude Direction Indicator (ADI) and five tests of cognitive performance. A functional Malcolm Horizon can also be displayed across the face of the panel. The main axis of the rotary device is centered in a 50-ft diameter white visual surround for presentation of patterns and targets external to the cockpit. The overhead projector set displays earth-fixed scenes and patterns on the visual surround. An "on board" projector set can project targets at different angular displacements relative to the subject in the cockpit. Motion characteristics about pitch and roll axes and changes in visual displays (cockpit and external target) are under computer control. In the cockpit, the "pilot" can fly by instruments and counteract computer control of the motion device. The computer provides immediate assessment of "man-in-the-loop" performance.

The two scenarios selected for development on Dynasim were formation flight and the "leans." The most frequently reported form of spatial disorientation (9) is the "leans." Formation flying, which has for the past 8 years accounted for the most Class-A pilot factor mishaps in the United States Navy (10), is the best maneuver to examine spatial awareness because it involves a high-intensity pilot workload with attention split between aircraft, cockpit, objects in space, and the Earth.

Two scenarios for demonstration of the leans are being compared to ascertain their relative effectiveness. In the first, a Dynasim pilot is placed in tangential forward-facing configuration at constant angular velocity with the wings level. The pilot perceives a roll to outside of turn and is given the controls and attitude indicator to be made aware of the leans and to correct his attitude by instruments. He is then given visual reference, which facilitates correction of attitude error and reduces the leans. In the alternate leans demonstration, the pilot at constant angular velocity is appropriately banked such that his Z-axis is aligned with the resultant of the gravito-inertial force (i.e., perceptually straight and level). When given the controls and cockpit instruments, the pilot must then concentrate on overcoming not only the disorientation associated with the "leans" but also that produced by rolling to "upright" in a plane perpendicular to the plane of rotation. During corrective actions, the visual surround is presented to reduce the leans and facilitate overriding the leans.

Formation flying as a wingman is a skill that demands such complete attention of the pilot to his lead aircraft that little or no time can be devoted to monitoring his own instruments. With little opportunity for instrument crosscheck, the wingman tends to assume in steady state flight that the lead aircraft is straight and level, particularly when deprived of visual reference to earth as during formation flying in weather or at night. The formation flying scenario is accomplished by projecting onto the 360° surround the wing aircraft on which the Dynasim pilot tries to maintain a constant relative position. In one scenario, we commence rotation with the pilot pre-positioned in roll so that the resultant force aligns with the Z-axis only after a constant velocity is attained. The pilot requires about 40 seconds to feel straight and level, apparently reflecting a lag effect (11).

In another more realistic scenario, we maintain Z-axis alignment throughout the initial acceleration and constant velocity. Here, we have encountered the leans, apparently from memory of the actual roll during the initial acceleration. We anticipate that this can be corrected by presenting a veridical external reference. Then, by reducing chamber illumination and by projecting an aircraft image onto the surround, the pilot soon perceives himself and his companion craft in level flight. Frequent but small changes in pitch and roll of the pilot's cockpit generate relative movement of the wing aircraft. Maintaining position demands full attention from the pilot to override computer generated pitch and roll. When the projected aircraft is directly off wing of the Dynasim pilot, large gaze-shifts (and large head movements) are necessitated while transferring attention between cockpit and target aircraft. These introduce a combination of cross-coupled angular accelerations and G-excess effects either of which can induce nausea in some subjects.

Two options for reducing this unwanted disturbance are lowered angular velocity and changing the average angular position of the companion aircraft to a more forward sector, thereby reducing the arc of gaze-shifts demanded from the pilot. Reduced angular velocity reduces the magnitude of the orientation error that the pilots will experience and may reduce the impact of the training. We are currently working on an acceptable compromise between offset angles and angular velocity.

In these scenarios, after the pilot has developed the erroneous perception of straight and level while flying the Dynasim, we can suddenly provide alternating glimpses of the wingman and a veridical visual reference quickly followed by demand to fly by instruments in breakoff from formation flight. The introduction of sudden breakoff, a phenomenon not infrequently encountered in formation flight, then places the pilot perceptually in a pitch and roll not matched by instruments, which requires considerable mental effort to maintain straight and level flight.

At this writing, we are developing prototype training scenarios in stage one of our program. Performance assessment during the scenario development will lead naturally into stage two, which consists of evaluation of new concepts in instruments displays.

The Dynasim by virtue of its unique disorientating capabilities is a suitable device to introduce pilots to new orientation displays because a comparison of the pilot's ability to maintain or recover orientation can be made under highly controlled conditions including a standardised workload. A limited number of pilots have been introduced to the Malcolm Horizon (a peripheral vision display consisting of a gyro-stabilized laser beam projected onto the instrument panel). Although the Dynasim has proven effective as a tool to assist test pilots in the development of the skill necessary to utilise their peripheral vision to monitor aircraft altitude, the Malcolm Horizon has not been well accepted by the operational community. There was a tendency by fleet pilots to stare at the peripheral vision display utilizing it as an altitude indicator (12). The introduction of any device that involves a change in long-ingrained skills will not be easily accepted by seasoned pilots. This illustrates the value of developing training paradigms to facilitate acquisition of new skills.

DISCUSSION

A drawback of flight simulators is the opportunity to develop and adopt strategies, which although effective in the simulator may prove to be disadvantageous on transfer to the aircraft. Although not a strong stimulus in our scenario, the G-excess illusion (13) may contribute significantly to this disorientation in commercial devices rated at 2 or more Gs. When head movements are disconcerting to a pilot due to a combination of G-excess and cross-coupled stimulation, the pilot will tend to avoid or minimize the motion-generated stimulus by making smaller head movements with larger deviations of gaze. Although still effective in maintaining awareness under the condition presented by the Dynasim, such movements are not necessary in the aircraft environment where the cross-coupled effects are reduced due to the large turning radius and thus reduced angular velocity.

Workshops and symposia directed towards the solution of situational awareness (14,15) and spatial disorientation repeatedly point out that the sensory channels of hearing, ambient vision, and proprioception have not been adequately utilized. In addition, the utilization of nonfoveal sensory channels to maintain aircraft situational awareness will release the central visual system to focus on aircraft information that can only be obtained through central vision.

Most spatial disorientation accidents are not due to radical maneuvers. Rather, they occur when periods of visual distraction from instrument scanning such as during intense concentration on cockpit emergencies or external targets permit the appreciation of non-veridical tactile and vestibular stimuli. The greatest contribution to biologically improve aeronautical spatial orientation will be the presentation of attitude information via a sensory channel that will permit continuous uninterrupted accurate information in a form readily and naturally assimilated by the central nervous system to supplement the intermittent data available from central vision. In the day-to-day terrestrial environment, the vestibular and kinesthetic/tactile channels provide this independent accurate redundant information. The difficulty arises in transferring to the aviation environment where both vestibular and other proprioceptive senses register inaccurately due to the continuous fluctuation of the resultant gravito-inertial force as well as illusions produced by prolonged rotations far outside the range of natural motion experienced on the ground. Among the primary sensory channels normally responsible for orientation the vestibular system is not readily accessible, which leaves the kinesthetic tactile channel and secondarily the auditory system as candidates to aid the visual system in orientation.

The kinesthetic tactile system has proven the most difficult to examine and determine its relative contribution to orientation. Whereas, the visual and auditory channels can be readily manipulated including shutting on or off and the vestibular system contribution determined using labyrinth-defective individuals, the kinesthetic tactile system cannot be easily isolated or manipulated even in animals without radically altering the biological system. Indeed, the omnipresent kinesthetic tactile information interacts so richly with the vestibular auditory and visual systems that it is often the confounding variable in psychophysical studies on orientation perception.

On Earth, the vestibular system standing alone can only ascertain orientation of the head, but when acting in conjunction with kinesthetic and tactile information can readily orient the individual to his body and earth or the vehicle into which he is strapped. This close relationship beginning even at the level of the first central nervous system relay suggests the opportunity to influence or override the erroneous aeronautical vestibular information with artificially applied veridical tactile inputs. The kinesthetic tactile system, which was once heavily stimulated in the aviation environment, has been progressively isolated over the past 50 years with the introduction of closed cockpits, reduced force feedback on controls secondary to fly by wire technology, and significant reductions in vibration levels with seat and airframe design improvements. For this reason, the tactile channel is the most logical choice to introduce supplemental orientation information.

One primary purpose in developing the two spatial disorientation paradigms is to permit the evaluation of the effectiveness of nonfoveal sensory channels in maintaining situational awareness either alone or in conjunction with standard displays. In particular, a one-to-one mapping of the external environment onto tactile fields is planned, utilising a combination of tactile illusions to present and move the stimulus with a limited number of stimulators. Although signal reliability and speed of response can be improved by additional information channels, the possibility of multisensory conflict exists. When will tactile proprioception and/or audition enhance visual contribution to orientation perception, and under what circumstances will saturation of information decrease performance or appreciation of orientation? The answers to these questions, to be evaluated in part on the Dynasim, will determine the products developed for future man-machine interfaces to solve or ameliorate the long-standing problem of situational awareness.

Recommendations and Objectives

1. Continue ground-based training utilising demonstration trainers (like MSDD) but with improved quality of demonstrations. Motion stimulus should not evoke symptoms of motion sickness. Focus verbal training pattern on maintaining orientation awareness and disorientation prevention; avoid "amusement park" demonstration. Training should immediately precede inflight disorientation demonstrations with routine scheduled refresher training every 3 years.

2. Develop closed-loop ground-based trainers that focus on the most likely inflight disorientation scenarios. Avoid rigorous conditioning-type training because of the possibility of transferring negative learning to the aircraft. More research is required in this area. Emphasise the maintenance of orientation awareness. This training should precede aerobatics and formation flight training with refresher training every 3 years.

3. Use man-in-the-loop formation flight scenario to develop prototype devices utilising nonfoveal sensory channels to maintain orientation awareness.

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14. Abstract

These Proceedings include the Keynote Address and 21 papers from the Symposium sponsored by the AGARD Aerospace Medical Panel, held in Copenhagen, Denmark from 2nd—6th October 1989.

The Symposium examined aviator situational awareness with consideration of conditions where problems occur, methods to assess situational awareness and latest methods for information management and presentation in the cockpit. Indications for future research needs were discussed. These Proceedings will be of interest to those involved with human perception and cognition and those responsible for design of modern aircraft cockpits. Keywords

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