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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Safety Network to Detect Performance Degradation and Pilot Incapacitation

(Réseau de Sécurité pour Détecter la Dégradation des Performances et la Défaillance du Pilote)

[redacted]

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.490

Safety Network to Detect Performance Degradation and Pilot Incapacitation

(Réseau de Sécurité pour Détecter la Dégradation
des Performances et la Défaillance du Pilote)

Papers presented at the Aerospace Medical Panel Symposium
held in Tours, France, on 2nd April 1990.

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Preface

In the predicted combat environment for future single-seat fighter aircraft, it is expected that the pilot will be exposed to a high mental workload and physiological stresses which may induce total or partial incapacitation. It is envisaged that support systems will be required to enable the pilot to function effectively in this environment.

It has been reported that G-induced loss of consciousness (G-LOC) has led to the loss of aircraft and aircrew. Furthermore, it is believed that combat effectiveness has been reduced by pilot performance degradation, caused by the high workloads imposed by manipulating the aircraft systems. The "Safety Net" concept, purports that a system could be devised which can initiate a temporary override in pilot authority until such a time as the pilot is able to resume full control of his aircraft.

The development of such a system, rests upon the premise that real time measures, which can indicate the onset of G-LOC or performance degradation, can be derived and used as inputs to such a safety net system.

The Aerospace Medical Panel (AMP) of AGARD considered it to be timely to review the current status of the relevant research and technology, and to provide a platform for the discussion of the pertinent issues which might affect the development of such systems.

Préface

L'environnement de combat du futur chasseur monoplace imposera au pilote une charge de travail intellectuel élevée ainsi qu'un stress physiologique pouvant conduire à l'incapacité patielle ou totale de ce dernier. Des sytèmes de soutien sont envisagés pour permettre au pilote de poursuivre sa mission de facon efficace dans ces conditions.

Des cas ont été signalés où la perte de connaissance sous l'effet de l'accélération de la pesanteur (G-LOC) a causé la perte de l'appareil et de son équipage. En outre, il y a lieu de croire que l'efficacité opérationnelle est réduite, en raison de la détérioration des performances des pilotes due aux charges de travail élevées imposées par la manipulation des systèmes avioniques. La notion d'un "réseau de sécurité" implique la réalisation d'un système qui permettrait le surpassement provisoire de l'autorité du pilote jusqu'au moment où celui-ci serait en mesure de reprendre les commandes de son appareil.

Le développement d'un tel système repose sur la supposition selon laquelle des mesures en temps réel, susceptibles d'indiquer la montée en G ou la détérioration des performances, peuvent être déduites et utilisées par la suite pour alimenter un tel réseau de sécurité.

Le Panel AGARD de Médecine Aérospatiale a jugé opportun d'examiner l'état d'avancement des travaux de recherche dans ce domaine ainsi que les technologies disponibles, afin de créer un forum pour la discussion des questions qui pourraient influencer le développement de ces systèmes.

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* To be included in the Technical Evaluation Report, Advisory Report, AR 301.

THE SAFETY NETWORK IN AN OPERATIONAL ENVIRONMENT

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INTRODUCTION

I believe it sensible to begin this address by outlining my professional credentials, since I am unknown to the majority of those present here today. Currently, I am serving at the Royal Air Force Institute of Aviation Medicine as a Test Pilot. My front line flying background has been as an air defence pilot, flying both single and 2 seat aircraft, with a total of 9 years experience. My main specialist role has been as a military test pilot and, currently, I have 10 years experience. During my flying career I have flown 31 aircraft types and achieved a total of 5300 hours, mainly on fast jet aircraft.

Turning to the subject of the symposium, it will, I am sure, come as no surprise to you that the initial response of the majority of military pilots to the concept of the Safety Network is virtually guaranteed to be negative. Military pilots are deeply sceptical with regard to the reliable, correct and safe operation of such advanced systems; particularly once they are removed from the flight test environment and are exposed to the rigours of front line operations. For instance, many pilots have experienced some very unpleasant situations resulting from aircraft autostabilisation system malfunctions. Such systems are deliberately designed with a very limited control authority, so a full authority system has the potential to seriously spoil a pilot's day.

Anticipated advances with performance degradation and incapacitation sensing systems coupled with modern aircraft flight control systems will undoubtedly provide the means to develop a workable safety network system. But the average military pilot will require a great deal of convincing that the advantages of the system will significantly outweigh the disadvantages that are likely to be present.

I will now briefly discuss specific items that I consider to be relevant to my thoughts. I emphasise that I am remaining strictly within the scope of the operational flying environment and am making no attempt to consider the flying training environment.

CONSIDERATION OF OPERATING ENVIRONMENT

Essentially, operational military aircraft fly within 2 environments, peacetime and wartime. The lessons of history clearly show that the realities of combat rarely match our anticipations. Aircrew inevitably have to operate their aircraft in a totally different manner to their previous peacetime operational training experiences. Therefore, I have some doubts regarding the role of a safety network system during operational wartime sorties. Any system that uses aircraft parameter cues, such as low aircraft height or the exceeding of aircraft speed limits, as part of the triggering sequence will be obsolete on Day 1 of a war. Assuming pilot incapacitation, what aircraft recovery manoeuvres could be used during wartime? There is no point in presenting a straight and level target for the enemy to engage. The aircraft system would initially be required to maintain any previous evasive manoeuvring, then to respond sensibly as current threats were cleared and new threats were presented. Basic responses to threats detected electronically can easily be programmed, but threats normally perceived by the Mk 1 eyeball would remain undetected and the necessary system response would not occur. Under certain circumstances the system might be able to allow pilot recovery following a short term incapacitation during an operational sortie. However, it is difficult to define such situations since incapacitation implies some form of enemy engagement and the engagement would surely continue. A longer term incapacitation would obviously be even more problematic. Could we anticipate the aircraft attempting to complete its preplanned mission? If this were truly possible then an extremely complex system would be necessary and, as a sideline, I would expect an immediate revival of the old arguments for pilotless aircraft. I submit that the role of a safety network system in wartime would be very limited. We should certainly await the availability of hard facts, following an extensive flight test programme, before considering the viability of anything more than a limited wartime role. Consequently, I believe the benefits and usage of a safety network system must lie, initially, within the scope of peacetime operational training. The situation is analogous to the 2 engines versus 1 engine argument with respect to fast-jet military aircraft. There is ample evidence that many aircraft have been saved from loss in peacetime by having the redundancy of 2 engines. But, once wartime battle damage is considered the advantages of a 2 engine configuration are significantly reduced with regard to aircraft survival.

When considering the peacetime environment there is one particular incapacitating situation that provides a clear and obvious reason for considering a safety network system and that is G-LOC.

G-LOC

G-LCC has been identified as a major threat to military pilots since the introduction, and subsequent build up, of highly agile aircraft capable of achieving, and sustaining, high levels of positive G_z. There is reliable evidence that some 10-12 military pilots have already been killed due to G-LOC incapacitation. In addition, there are many G-LOC related incidents reported every year which, thankfully, have not resulted in fatalities. Consequently, military pilots can readily see and understand the need for greater protection in this particular area. Obviously, enhanced G protection systems comprise one such protection option already under development. There can be little argument that the development of a safety network system designed solely to provide safe recovery following G-LOC incapacitation deserves every encouragement. The facts speak for themselves, and the likely costs of failing to resolve the problem, both in pilot fatalities and aircraft losses, will be high.

PILOT INCAPACITATION DUE TO OTHER CAUSES

The RAF has evidence that a small number of accidents and associated fatalities can be attributed to other causes of pilot incapacitation. This incapacitation was due either to medical conditions or as the result of an external source eg aircraft collision. Whilst it would be unlikely that a safety network system could cope with the associated control problems consequent to most aircraft collisions, the safe recovery of a pilot suffering from a medical incapacitation should be feasible. Incapacitation due to hypoxia is always a possibility, although the RAF has no recent experience of any accidents/fatalities due to this cause.

BASIC RESERVATIONS

Notwithstanding my previous comments, I reiterate that there will be significant military pilot reservations to accepting such a system. I will now discuss what I believe will be the main areas of concern for military pilots.

a. Aircrew Equipment Assemblies. Military pilots are already heavily overloaded with flying clothing, survival aids and helmet mounted devices. The requirement to wear so much equipment causes discomfort and, dependent upon ambient air temperatures, heat stress problems can occur. The sheer bulk of the clothing and equipment seriously impairs mobility, both internal and external to the cockpit. The time taken to dress correctly for flight is becoming longer and in some situations the pilot actually requires assistance to don the equipment. The need to include NBC protection significantly exacerbates the problem. You must expect that the addition of even more equipment, such as bodily mounted sensors, to detect pilot performance degradation or incapacitation will be strongly resisted, unless the equipment is totally unobtrusive and does not require tiresome donning procedures. Any requirement for pre-flight testing of the system must be minimal.

b. Functions Triggering the System. System trigger functions will require careful consideration. Reliable sensing of total pilot incapacitation would provide an obvious, unambiguous trigger. I anticipate that the difficult problem areas will be associated with reliably determining incipient or partial pilot incapacitation and, particularly, measuring pilot performance degradation. Individual pilots employ a wide spread of techniques to fly and operate their aircraft to achieve the same task or result. I suspect this factor will make it very difficult to define a level at which performance is considered to be degraded and a safety network system triggers. A possible system based on the monitoring of control activity surely requires some template or standard to compare against. I suspect that there is no such usable standard capable of being determined within the pilot community. Within the military environment flexibility is the key to everything; hence, anything defined today will probably be out of date before it can be incorporated into a flying system.

c. False Alarms. False alarms, or other system malfunctions, will alienate the system to pilots. Clearly, there are situations whereby the triggering of the system by a false alarm could even be hazardous. Two specific situations come to mind, namely, aircraft flying in close formation or engaged in slow speed, close range air combat manoeuvres. They could be particularly vulnerable to mid-air collision following a false system trigger. Any problems within this area would simply result in pilots flying with the system switched off.

d. Definition of Recovery Manoeuvres. Once the system is triggered what will determine the optimum recovery manoeuvre? Would it be possible to define a single recovery manoeuvre that would be acceptable for all anticipated circumstances? Personally I doubt it, since there would be too many variables involved. The system will need to compute its recovery manoeuvre having consideration for, at least, the aircraft's current flight parameters, the current rates of change of those parameters, the aircraft's current aerodynamic capabilities and the capabilities of the flight control system. These requirements will generate a significant software programming and computing task and military pilots have good cause to be circumspect about the correct operation of such systems. Whilst a recovery manoeuvre to straight and level flight would be acceptable for short term incapacitations, eg G-LOC, for longer term incapacitation, eg serious intercurrent illness, full recovery of the aircraft to a runway, or even an aircraft carrier, would be required.

TESTING THE SYSTEM

If the development of the system proceeds, I anticipate considerable difficulties in achieving adequate and fully representative flight testing of such a system. Designing suitable trials to confirm the correct operation of the performance degradation detection modules would, I suspect, be taxing. Finally, what would be the extent of the system/software tests required to satisfy the normal airworthiness safety requirements.

CONCLUSIONS

I have deliberately expanded my discussions to include factors outside of your particular specialities. Military pilots look at the complete picture to determine their response to any new systems. I appreciate your interests lie predominantly within your own specialist fields, but you must always be aware of the additional problems that must be solved if the safety network system is to proceed beyond the experimental stage. I am sure that military pilots generally will come to accept that the concept of a safety network system is sound. However, all too often advanced systems enter service with capabilities that fail to match up to the initial proposals. I would strongly recommend concentration on a system designed to provide protection from G-LOC incapacitation rather than the more complex possibilities. In the final analysis, military pilot acceptance of a safety network system would be based, as always, on the following:

a. Do I really need such a system and will it be a safe and reliable system?

b. What additional equipment will I need to wear and how will that affect my comfort and mobility?

c. Will it make the successful achievement of my primary flying tasks easier or more difficult?

Ladies and gentlemen, I hope that I have explained the operational pilot's views to you clearly and without appearing to damn the safety network system. I am sure that the system has potential, but I urge you all to resist any temptation to promote the development of an overly complex system.

Navy Aircrew Opinion of Pilot Monitoring and Recovery Systems

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SUMMARY

Navy tactical pilots and NFO's were provided a multiple-item questionnaire with instructions to indicate flight history and other demographic information, and to respond to close-ended queries about a theoretical, generically defined, pilot monitoring advisory and recovery system. The queries were designed to ascertain user opinion of system acceptability, tactical viability, and other merits or shortcomings. Respondents also provided illuminating commentary. There was guarded acceptance of PMRS, more so among senior, more experienced officers, despite general opinion that GLOC is not a problem in fleet or training operations, that a safety net device would likely be burdensome and not of fully trusted reliability, availability, or tactical utility. Acceptance was generally higher for a system which (1) would recover the aircraft from an uncontrolled flight path (vs. merely advising pre-LOC), (2) provided an on/off selection capability, and included in addition, (3) a selectable "soft deck," absolute altitude, to warn the aircrew of impending GLOC, and (4) a selectable "hard deck," absolute altitude, to initiate flight path recovery. Given optimal engineering solutions (system reliability, etc.), the officers expressed strong (junior officers) to very strong (senior officers) approval for PMA/RS, introduced no earlier than at the Fleet Readiness Squadron level, despite universally conservative estimates of potential tactical improvement afforded by the system.

LIST OF SYMBOLS and TERMS

PMAS:	Pilot Monitoring and Advisory System
PMRS:	Pilot Monitoring and Recovery System
MTBF:	Mean Time Between Failures
GLOC:	G-Induced Loss of Consciousness
0-2:	Lieutenant (Junior Grade)
0-3:	Lieutenant
0-4:	Lieutenant Commander
0-5:	Commander
FRS:	Fleet Readiness (Training) Squadron

INTRODUCTION

Of fundamental importance to the successful development of any on-board pilot monitoring and recovery system (PMRS) is the effective integration of the system within its complete tactical context--i.e., within the aircraft's mission supersystem. Adequate representation of the mission supersystem entails analysis not only of essential engineering and safety issues, but of training ramifications, operator employment, and tactical utility. In the case of PMRSs, the supersystem is a multi-dimensional one. Included are hardware, software, the interaction of hardware and software with "organware," the logistical support trail, and very significantly, the tactical and doctrinal "drivers" that can determine whether the incorporation of the proposed system will ultimately represent a significant, net improvement in the weapon supersystem.

Formal evaluation of all aircraft modifications including PMRS--in the context of mission tactics--is not typically performed until Operational Test and Evaluation stages of the acquisition process. Here, tactics and PMRS will be assessed and honed, until final recommendations are derived, and decisions for fleet introduction are made. The final product will most certainly not be isomorphic with the original design. Rather, the PMRS candidate AND associated tactics will undergo iterative adjustment until a satisfactory composite is achieved. During test and evaluation, the tactical contribution of PMRS will be given extensive consideration.

Significantly, the design community must understand that PMRS--as any aircraft improvement product--MUST be regarded as a mission enhancement, envelope expansion, or like upgrade to the supersystem. Expressed the other way, PMRS must NOT be regarded solely as an augment whose purpose is to remove a behaviorally avoidable, even if deleterious aspect of mission accomplishment. This precept has revealed itself historically, and will likely continue, particularly in economic circumstances of finite or decreasing resources. Thus, the safety net must be engineered as a weapon improvement rather than merely as a safety net.

None-the-less, a comprehensive view of the supersystem includes a look at the negative factor, viz., G-Induced loss of consciousness (GLOC) and the degree to which this treacherous factor "pulls" PMRS. First, is the rather unequivocal issue of GLOC incidence. Figure (1) provides an indication of the frequency of Class A accidents which were concluded to be GLOC associated for U.S. tactical aircraft between 1982 and present. The figures are regarded as conservative, since GLOC is very difficult to confirm in Class A accidents. Clearly, even with conservative data, GLOC occurs, and it appears analytically to be a significant threat in high performance aviation.

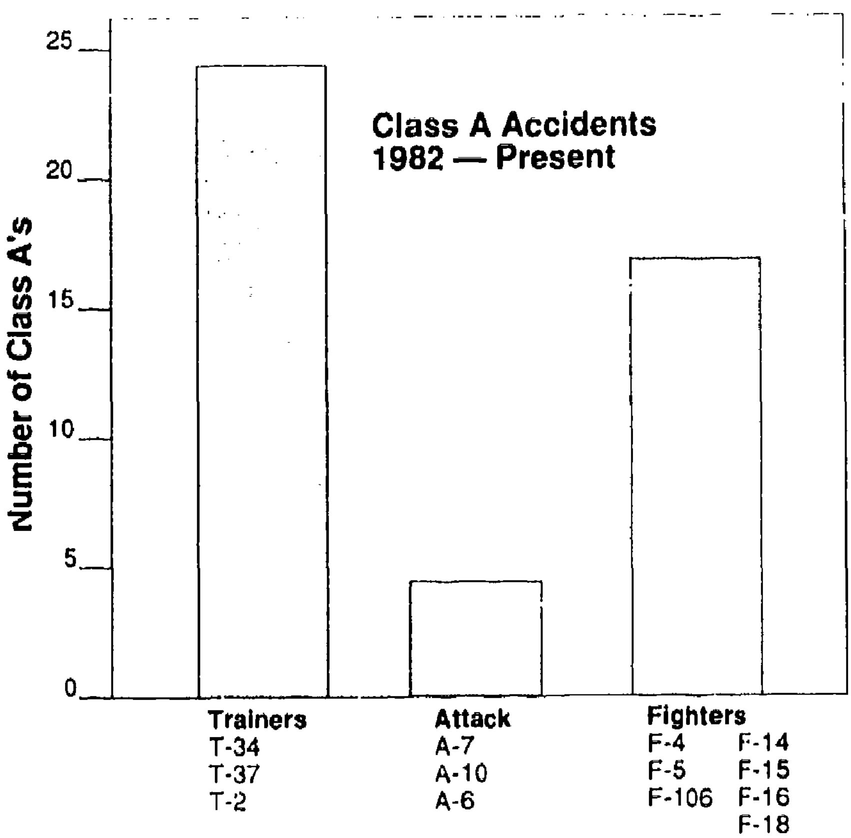

Figure 1. Numbers of Class A accidents in U.S. aircraft from 1982 to present.

Second, and perhaps more importantly, is the perception of G/GLOC threat among aircrewmen. The G "threat" can be considered as two-fold: Mediated and absolute. The <u>absolute</u> threat is a function of the actual limitation of aircraft structures and human physiology to instantaneous and sustained G. This limitation should be regarded more as a defensive than an offensive limitation; none-the-less the limitation is in fact a written, "legal" one. As is shown in Figure 2, the solid line indicates the level of safe aggressiveness afforded with current G protection, and thus the turning limitations imposed by the G/GLOC threat.

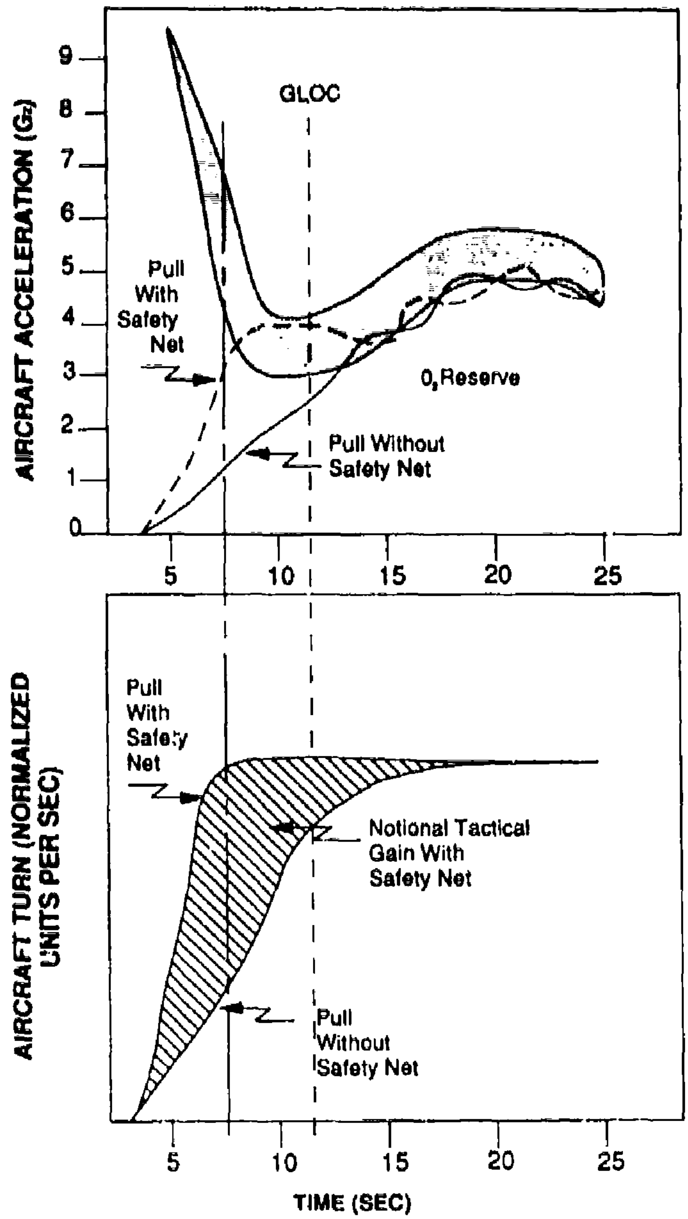

Figure 2. Notional advantage gained for tactics with safety net This advantage obtains only if the pilot believes it.

The mediated threat, on the other hand, is characterized as a perceptual one; it is more an offensive than defensive limitation. The notion here is that the pilot will seek to avoid not only breaking his wings, but also losing consciousness, because in either case the outcome is disastrous. This G buffer limitation suggests that without a "safety net," the pilot simply will not fly as aggressively in an offensive mode as he would fly with a net. With respect to Figure 2, then, the pilot without fear of the consequence of PMRS is one who "flies" the solid bold lines.

The present effort sought to derive a better understanding of G/GLOC buffers and limitations, and of the ramifications of introduction of PMRS machinery into the mission supersystem. This was accomplished by collecting and evaluating the opinions of experienced fleet aviators.

METHOD

Navy tactical pilots and flight Officers (NFOs) were provided a multiple-item, multiple-choice questionnaire, with instructions to indicate, anonymously, flight history information, and other relevant demographical information. The 23 close-ended queries (15 questions with 8 sub-questions) were to be answered with two hypothetical PMRS designs in mind. The first was one which detects GLOC or near-GLOC, and warns the aircrew. The second detects GLOC, warns the aircrew for some period of time, and then recovers the aircraft until the point of pilot override. The questions were designed to ascertain general opinion about user acceptability, tactical viability, and other potential merits or shortcomings. The respondents were also asked to provide open-ended commentary on key specifics associated the introduction of PMRS. (The survey questions are disclosed in the Findings section.)

FINDINGS

The demographical characteristics of the respondents are summarized in Table 1.

TABLE 1

	Low	High	Mean	Mode
Rank	0-2	0-5	----	0-3
Flt. Hrs.	375	3,700	1,520	----

There were 26 pilots and 12 NFOs among the respondents; 24 junior (0-2, 0-3) and 14 senior (0-4, 0-5) officers. No respondent disclosed having ever experienced GLOC.

Results of the substantive questions are indicated below. The bold entries indicate modal responses for junior officers; italics for senior officers. Selected commentary is appended to each item. The commentary was taken from respondents who answered the particular question with the mode, or in some particularly interesting way.

1. Do you think G-induced loss of consciousness (GLOC) is a problem in fleet (TACAIR) operations?

	Strong No		No	Neutral		Yes	Strong Yes
	1	2	3	4	5	6	7
SUM	2	6	6	10	6	6	1

COMMENTS, selected response preceding, officer rank following.

4, Occasionally we lose an aircraft/aircrew to the problem. (0-5)

3, Fleet pilots apply g by feel. The more experienced pilots will not let the onset of g exceed body limits. The only time it is a problem is when inexperienced pilots are too rough and apply g too quickly. (0-4)

4, I never met anyone who experienced GLOC. (0-4)

2. Do you think GLOC is a problem in the training pipeline?

	Strong No		No	Neutral		Yes	Strong Yes
	1	2	3	4	5	6	7
SUM	3	4	5	11	10	4	1

COMMENTS:

4, Once aware of it in the Fleet Replacement Squadron it was not a problem. Really was not addressed in the training command. Should be an item for the tactics phase of advanced jet NFO training. (0-4)

5, A few problems in ACM with students. M-1/L-1 techniques are not emphasized as much as they could be. (0-5)

4, I never met anyone who experienced GLOC. (0-4)

3. Do you think that aircraft structural g limitations (e.g., 6.5 for F-14) are a problem in potential fleet combat operations?

	Strong No		No	Neutral		Yes	Strong Yes
	1	2	3	4	5	6	7
SUM	2	3	4	2	4	11	13

COMMENTS:

6, Too low! Need a high g capable aircraft. (0-4)

7, We need to have the capacity to turn with the current threat aircraft. We have the engine in the F-14A+ to perform with, now we need the airframe to rate with the threat aircraft of today and tomorrow. We need at least 7.5 g's. (0-4)

4. If more g were available, would you use it to tactical advantage?

	Strong No		No	Neutral		Yes	Strong Yes
	1	2	3	4	5	6	7
SUM	0	1	1	0	3	9	24

COMMENTS:

7, For missile defense and defensive maneuvering. (0-4)

7, I don't need 8.5 g's in non-combat situations. 7 to 7.5 g's would be nice to practice with for physical appreciation and training, and for heightened awareness of the functional (human) limits under sustained high g's at 8 to 9 g's. (0-4)

5. If more g were available, and fleet aviators routinely used it, would GLOC become a problem?

	Strong No		No	Neutral		Yes	Strong Yes
	1	2	3	4	5	6	7
SUM	1	3	3	7	10	11	2

COMMENTS:

5, Initially, however as time passes aviators would adjust. (0-4)

5, It could if proper preparation and conditioning weren't accomplished. (0-4)

5, We need to train ourselves physically to handle the demands on our bodies in high g's. If we don't get serious here we could get into trouble with GLOC. (0-4)

7, Mainly due to lack of g tolerance, due in part to lack of regular high g type flying. The aircrew think they have the physical capacity to tolerate high g. (0-4)

5, May be hard to get sufficient onset rate in non fly-by-wire aircraft to induce GLOC. (0-4)

6. Do you think that human g tolerance limitations are a problem in potential fleet combat operations?

	Strong No		No	Neutral		Yes	Strong Yes
	1	2	3	4	5	6	7
SUM	3	6	9	2	10	6	2

COMMENTS:

5, Not now, but depends on how advanced tactical aircraft become. (0-4)

7. Pilot monitoring and advising systems (PMAS) are technologically feasible. PMAS would monitor pilot state [either with bio-medical sensors, or by inferring pilot state based on computer analysis of pilot control inputs (or lack of)]. Having decided that the pilot is incapacitated, PMAS would alert (e.g., with loud warning sounds) the aircrew. What is your opinion of such a system?

a. Strongly Distrust Validity (false positives too high)	Distrust		Neutral	Trust		Strongly Trust Validity (false positives ok)
1	2	3	4	5	6	7
SUM: 9	2	7	13	2	1	1

COMMENTS:

4, Might rate a score of 5 if there are no false alerts. (0-4)

4, Though unfamiliar with the system, initially feel that it is a good idea. I wonder if the pilot could hear the warning under GLOC. (0-4)

3, Good education on g tolerances would be as good. Too many bells and whistles already. (0-4)

4, Very dependent on what you use it as. A warning tone will not accomplish much in an F-14. If the plane is suddenly not maneuvering, the RIO will start talking to the pilot. No response from the pilot would indicate he's unconscious. The RIO cannot fly the aircraft unless the pilot recovers, and ejection would be required. Some sort of auto leveling option in the autopilot would be necessary. Blackout would trigger PMAS which would trigger the quto leveling. (0-3)

b. Strongly Burdensome (to pilot)	Burdensome		Neutral	Transparent		Strongly Transparent (to pilot)
1	2	3	4	5	6	7
SUM: 3	1	13	12	3	0	2

c. Strongly Distrust System Availability (low MTBF)	Distrust		Neutral	Trust		Strongly Distrust System Availability (high MTBF)
1	2	3	4	5	6	7
SUM: 1	6	10	15	1	0	0

d. Strongly Disadvantageous Tactically	Disadvantageous		Neutral	Advantageous		Strongly Advantageous Tactically
1	2	3	4	5	6	7
SUM: 3	3	9	16	2	1	2

COMMENTS:

4, I would look at PMAS more from a training aspect (fewer losses in training) than as a combat tool. (0-5)

e. Strongly Distrust Reliability (fail to detect GLOC too often)	Distrust		Neutral	Trust		Strongly Trust Reliability (almost never fail detect GLOC)
1	2	3	4	5	6	7
SUM: 1	7	10	15	0	0	1

8. Pilot monitoring and <u>recovery</u> systems (PMRS) are also technologically feasible. PMRS would detect incapacitation, as in 7, above, but would, in addition, continuously calculate time to earth impact, and when a threshold is exceeded, cause the jet to fly straight and level until the pilot recovers control of flight path. What is your opinion of such a system?

a.

Strongly Distrust Validity (false positives too high)	Distrust		Neutral	Trust		Strongly Trust Validity (false positives ok)
1	2	3	4	5	6	7
SUM: 4	5	10	6	7	1	2

COMMENTS:

4, A false recovery could kill you in combat. (0-4)

3, Could be used as a crutch. (0-4)

6, I am not sure it would work but I have lost three close friends in F-16 GLOC accidents and feel something, even if it is not perfect, is better than nothing. (0-3)

b.

Strongly Burdensome (to pilot)	Burdensome		Neutral	Transparent		Strongly Transparent (to pilot)
1	2	3	4	5	6	7
SUM: 2	4	13	8	6	1	0

c.

Strongly Distrust System Availability (low MTBF)	Distrust		Neutral	Trust		Strongly Distrust System Availability (high MTBF)
1	2	3	4	5	6	7
SUM: 3	6	12	9	4	0	0

d.

Strongly Disadvantageous Tactically	Disadvantageous		Neutral	Advantageous		Strongly Advantageous Tactically
1	2	3	4	5	6	7
SUM: 5	4	9	12	3	0	2

COMMENTS:

3, A malfunction at the wrong time could be <u>very bad</u>. (0-4)

4, Not really tactically advantageous. You still can't afford to black out. Recovery straight and level makes you a sitting duck for the guy you were fighting. (0-3)

e.

Strongly Distrust Reliability (miss rates too high)	Distrust		Neutral	Trust		Strongly Trust Reliability (miss rates okay)
1	2	3	4	5	6	7
SUM: 2	7	5	11	6	2	2

9. If PMAS were selectable (on/off) what would your opinion be?

Strongly Dislike	Dislike		Neutral	Like		Strongly Like
1	2	3	4	5	6	7
SUM: 3	2	3	10	8	7	3

COMMENTS:

5, Like it "on" in training, off in combat (concerned about false alarms.) (0-5)

5, It might be appropriate for less experienced pilots like FRS pilots and first tour fleet aviators. (0-4)

10. If PMRS were selectable (on/off) what would your opinion be?

	Strongly Dislike	Dislike		Neutral	Like		Strongly Like
	1	2	3	4	5	6	7
SUM:	3	2	4	9	7	7	3

11. If PMAS coupled with PMRS were selectable (on/off) AND a soft deck (for auditory warning) and hard deck (for flight path recovery) altitudes were selectable, what would your opinion be?

	Strongly Dislike	Dislike		Neutral	Like		Strongly Like
	1	2	3	4	5	6	7
SUM:	2	1	2	8	6	12	6

COMMENTS:

6, useful in training. (0-5)

6, System shouldn't be selectable, but overridable. (0-4)

6, This idea sounds good. Combining warning and recovery is meaningful. Warning alone is not enough. (0-3)

12. If PMA/RS were engineered well, would such technology enhance the offensive capability of tactical jets?

	Strong No	No		Neutral	Yes		Strong Yes
	1	2	3	4	5	6	7
SUM	4	2	7	10	4	6	5

COMMENTS:

3, The pilot must decide what is necessary in a given situation, not a machine. (0-3)

13. Same as #12, but selectable (throttle or stick switch) commensurate with employment of high-G (or other) last ditch defensive maneuver?

	Strong No	No		Neutral	Yes		Strong Yes
	1	2	3	4	5	6	7
SUM	4	3	7	7	8	5	4

COMMENTS:

5, Selectable off, I don't want it in last ditch combat maneuvers. (0-5)

14. From a tactical point-of-view, would a reliable, valid, and available PMA/RS improve combat effectiveness (Pk, defensive maneuvering, bombs-on-target, etc)?

	Strong No	No		Neutral	Yes		Strong Yes
	1	2	3	4	5	6	7
SUM	6	6	10	8	3	3	2

COMMENTS:

2, If installed, no one should be put into the situation to require its use. Better basic aircraft, seat, g-suit design along with g tolerance training are better answers to the problem. (0-4)

7. It would not add any combat capability to the jet itself nor will it change pilot behavior during combat. What it will do is save lives and aircraft that we can use in the next war. In this way, combat effectiveness will be enhanced. (0-3)

2. Still feel it should not be used as a crutch. Pilots still need to fight their plane to the limits they are capable of but never exceed them. (0-3)

15. If PMA/RS were to be introduced, where in the pipeline makes the most sense?

PIPELINE

	T-34	T-2	TA-4	FLEET JET (training)	FLEET JET (operational)	Nowhere
Junior Officers	0	1	2	15	3	5
Senior Officers	1	0	0	10	1	0

DISCUSSION and CONCLUSIONS

The data collected indicate that there is an apparent guarded acceptance of the safety net concept. The acceptance is higher among senior, more experienced, officers than among juniors. Mild acceptance was inferred despite the fairly generally held belief that GLOC is not a significant problem in fleet or training operations. Whether GLOC is a significant problem is, of course, an opinion that is more important at policy levels than at fleet aviator levels.

The respondents indicated a desire to have more G legally (structurally) available, and that if it were, it would be used to tactical advantage. Afforded more "legal" G, however, the officers perceived that GLOC might become a significant fleet problem. The junior officers were more skeptical of the insidiousness of G, regardless of G available.

The participating officers were neutral about impending-GLOC ADVISORY-only systems. There was little demonstrable trust for PMAS validity (false positives might be excessive, which would be quite distracting), or reliability (too many misses). Similarly, PMAS was not perceived to be a welcomed logistical addition (system availability would not be high), and (though no physical description was provided to the respondents) PMAS was not predicted to be unburdensome. The tactical utility of a design-free PMAS was generally inestimable by the respondents. The attractiveness of PMAS improved if the theoretical system included a selectable "on/off" feature.

Pilot monitoring and RECOVERY systems were perceived to be more attractive than advisory-only candidates, though predominantly among senior, more experienced officers. Though not estimated to be particularly unburdensome, reliable, valid, or available, the senior officers preferred the PMRS with an "on/off" switch.

Sentiment for PMA/RS proved to be highest if, in addition to "on/off" selection, a soft deck [selected during flight preparation or situationally as absolute altitude (for the pre-G advisory)] and a hard deck [selected as absolute altitude (for flight recovery)] were afforded.

Provided with the best engineering solutions (presumably, the respondents inferred from the questionnaire that this meant acceptable reliability, validity, availability, and burden), the senior officers expressed strong acceptance. If selectability were also incorporated, junior officers indicated strong sentiment; senior officers indicated very strong approval. The provisional approval of a perfectly designed PMRS was provided by respondents despite only modest estimates of tactical value (e.g., improvement in kill probability). The almost universally nominated introduction point for a PMRS was at the FRS level--the pipeline point at which graduate aviators begin flying their first fully complemented aircraft (e.g., F-14, F-18) prior to assignment as a deployed, fleet aviator.

In conclusion, junior officers tended to view PMRS as an unreliable solution to a (safety) non-problem. Senior officers, on the other hand appeared to regard PMRS as a candidate avenue to improving airmanship. More generally, the data collected in the present study suggest cost-related design boundaries, and they suggest that a safety net might improve not only safety, but, perhaps, tactical success as well. Consideration of tactical variables introduces myriad, quantifiable factors. These factors must be examined fully.

Le concept de filet de sauvegarde
The safety net concept

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Résumé Le filet de sauvegarde est un système de récupération de situations par prise en main autoritaire-mais temporaire- du pilotage en cas de perte de connaissance du pilote ou de parade à fournir en urgence. Les problèmes posés sont de trois ordres: opérationnels (comment coupler un tel système à la situation), psycho-physiologiques (comment détecter l'état du pilote: perte et reprise de conscience) et informatiques (quelle architecture pour le système). L'article résume l'état des connaissances dans les trois domaines et suggère un série d'étapes intermédiaires avant d'arriver à un système possédant toutes les fonctionnalités (notamment en tournant les plus sévères difficultés par une restriction temps de paix et un système semi-automatique attendant des confirmations du pilote ; il est cependant probable qu'un système limité au temps de paix posera des problèmes opérationnels en temps de guerre (manque d'habitudes, effets de transfert négatifs, sur-confiance, etc). Quelle que soit le niveau de réalisation, la collaboration étroite entre les spécialistes des trois disciplines apparaît comme la clé du succès.

Abstract The safety net is a system designed to temporary override the pilot authority in case of the suspicion of pilot's loss of consciousness or in case of a needed reflex response to an immediate threat. Problems to elaborate such systems are of three natures: (i) operational (tasks requirements), (i) psycho-physiological (how to detect the pilot awareness : loss and return of consciousness), (iii)computational (system architecture). The paper summarizes the state of the art of these three mentioned above domains. Priority to peace time applications and systematic use of confirmation dialogues could logically result of the analysis of current goals and know-hows, but operational requirements (namely confidence effect and negative transfert) could in turn reduce the interest of using a limited peace time safety net system. Anyway, the key for success remains in a close cooperation between the various disciplines involved in the concept of safety net.

1-Introduction:

Le filet de sauvegarde peut-être défini comme un système de récupération des situations dans lesquelles le pilote est incapable d'assumer la direction du couple Homme-Machine (H/M), soit parcequ'il a perdu conscience (cas général du Gloc), soit parcequ'il ne dispose plus des ressources intellectuelles et motrices suffisantes pour parer à un péril immédiat (cas général des réponses reflexes à des missiles). Dans les deux cas, le problème d'incapacitation est évidemment temporaire, l'action d'un système est donc celle d'un relai visant à rendre les commandes à l'opérateur au plus vite.

Le développement rapide de ce concept (les premiers travaux remontent à peine à 1980) est dû à la mise en service d'avions de combat à hautes performances (A10, F16, F15, Mirage 2000, etc). Il s'inscrit dans le cadre plus général des études sur les systèmes d'aides embarquées basés sur une inversion du flux H/M : la machine prenant de l'information sur l'homme pour différents usages (dépistage d'erreurs, reconnaissance d'intention, copilote électronique) .

Dans tous les cas, la mise au point d'un tel système, capable de relayer efficacement le pilote au bon moment, suppose un triple compétence: en ergonomie-analyse opérationnelle (comment coupler un tel système dans le cadre de la tâche), en psycho-physiologie (évaluation de l'état du pilote) et en informatique (comment traiter le problème de l'indécision, quelle architecture). A ce jour, l'absence quasi-totale de théories sur les prémices cognitifs des pertes de connaissance interdit d'imaginer un système préventif, sauf à le rendre extrèmement pénalisant pour le domaine de vol tactique.

Le projet de filet de sauvegarde exige une collaboration entre les différents spécialistes sus-cités et la définition de compromis sur les objectifs (sécurité des vols/ efficacité en combat/ acceptabilité par les usagers). Ce sont précisément ces deux problèmes (coopération multi-disciplinaire et définition du compromis) qui ne sont pas maitrisés à ce jour et qui limitent le développement de systèmes concrets.

Ces trois compétences (ergonomique-opérationnelle, psycho-physiologique, informatique) articulent naturellement les chapitres du présent article. La première partie propose une classification fonctionnelle des différents types de filets de sauvegarde en fonction des objectifs dans la tâche (points de vue opérationnel); la seconde partie étudie plus particulièrement l'état de l'art en matière de diagnostic de l'état du pilote (point de vue psycho-physiologique) et la troisième partie analyse les architectures informatiques susceptibles de répondre au problème (point de vue informatique) .

2-Discussion sur les contraintes opérationnelles

Selon **Gillingham (1988)**, 7 accidents de F16 (Airforce) et 2 accidents de F15 (Navy) ont été causés depuis 1983 par des pertes de conscience du pilote. Le même auteur ajoute que 20 pertes de connaissances surviennent en moyenne chaque année en entrainement chez des élèves pilotes de T37; un questionnaire adressé aux pilotes opérationnels indique que 30% des pilotes de F16 aurait connu ce problème, et 14.3% des pilotes de la Navy. Ces chiffres, repris ou confirmés par d'autres statistiques de sources Européennes (**Clère & al,1987; Kuipers & al, 1989**) suffisent par eux mêmes à justifier les études visant à diminuer ces risques.

Le problème médical serait résolu si l'on acceptait de limiter les performances avions; il n'en est malheureusement pas question pour des raisons opérationnelles. On sait par ailleurs que la marge d'évolution des systèmes anti-g individuels est maintenant comptée; l'espoir ne peut donc venir que de la formation des pilotes (entrainement en centrifugeuse) et du développement de systèmes de filet de sauvegarde. Nous nous centrerons dans cet exposé sur cette dernière perspective tout en soulignant que les efforts devront nécessairement être réalisés également pour l'entrainement des pilotes, le filet de sauvegarde n'étant qu'un pis-aller (l'Armée de l'Air Française va bientôt être équipée d'une centrifugeuse d'entrainement).

De la même façon, les missiles disponibles sont devenus si performants que, surtout en cas d'épuisement des contre-mesures, les parades efficaces nécessiteront de plus en plus des trajectoires inductrices de pertes de connaissance. Là encore, le filet de sauvegarde apparait comme une réponse de pis-aller permettant ponctuellement de dépasser les limites psycho- physiologiques habituelles.

Quelle que soit l'application, les exigences opérationnelles d'un tel système de sauvegarde sont (i) de détecter le moment où il faut prendre les commandes, (ii) de gérer au mieux ces commandes en l'absence du pilote dans la boucle, (iii) de rendre les commandes au plus vite à un pilote redevenu efficace.

(i) La prise de commandes autoritaire peut-être envisagée sous un mode automatique ou semi-automatique.

En mode automatique, le niveau de réglage du système est crucial : en cas de mise en route par excès, le système désoriente sévèrement le pilote en limitant son champ d'action et son domaine de vol, voire l'engage dans des positions tactiques dangereuses; en cas de non-détection, le système perd son intérêt. Une éventuelle limitation au temps de paix élimine beaucoup de ces exigences: un système intervenant parfois par excès pourrait alors être acceptable, même s'il est désagréable; le temps de paix élimine également tout le domaine des parades réflexes.

En mode semi-automatique, un dialogue de confirmation systématique avec le pilote réduit considérablement les problèmes d'indécision: le système pourrait en effet, sur la base de paramètres ayant franchi un seuil critique, demander au pilote une confirmation de son état de conscience; la non confirmation dans un délai donné déclencherait le processus de transfert des commandes vers la machine.

(ii) Il en va de même avec la gestion des commandes:

Pour la perte de connaissance en temps de paix, chacun convient qu'un système de remise à plat, altitude non conflictuelle avec le terrain, est suffisant pour assurer la sécurité des vols. En temps de guerre, cette position en combat serait dramatique; il faut donc gérer la situation avion (trajectoire mais aussi état global des systèmes de l'avion) en fonction du contexte de combat, et idéalement poursuivre la manoeuvre engagée par le pilote pour diminuer le temps nécessaire à sa compréhension de la situation tactique une fois qu'il aura repris conscience (on sait que le pilote subit une amnésie quasi totale dans les Gloc, donc il raisonnera à la reprise de conscience sur la dernière situation qu'il a connu avant le Gloc).

Pour la parade de type réponse réflexe, le problème est d'effectuer cette parade dans le cadre de l'enveloppe physiologique du pilote, au pire, en lui faisant perdre conscience temporairement, et de toutes façons en évitant tout traumatisme (en particulier de la colonne cervicale).

(iii) Le remise des commandes au pilote peut-être envisagée sous trois modes ; à la demande (on attend que le pilote reprenne de lui même les commandes), en évaluant activement l'état du pilote (avec un système d'évaluation de la qualité de la reprise de conscience; cette solution vérifie que le pilote reprend les commandes dans de bonnes conditions de conscience), ou encore en fonction de la situation tactique; compte tenu de l'amnésie du pilote, il pourrait être géné pour comprendre, et donc pour poursuivre une manoeuvre engagée par un système à compétence tactique; le système pourrait donc attendre la fin de cette manoeuvre avant de rendre la main au pilote; il faut noter également qu'un gestionnaire tactique ne touchera pas qu'à la trajectoire; il pourra -ou devra- se servir du radar, des contre-mesures, de certaines ressources systèmes; en bref, il positionnera le système avion dans une configuration nouvelle dont il faudra rendre compte au pilote sachant que ce dernier raisonnera comme si rien n'avait changé (du fait de l'amnésie).

Ces différents niveaux de réalisation possible conduisent à cinq types de systèmes:

<u>Les systèmes de type 1</u> sont les systèmes de bases, encore appelés "recovery systems": ils ne s'appliquent que temps de paix et comportent une détection semi-automatique de perte de connaissance (supposant une interrogation directe du pilote) déclenchée sur des paramètres très simples à récupérer et non invasifs (jolt, g, attitude avion, pression commandes, position tête, etc) ; le système effectue une remise à plat autoritaire et une recherche d'altitude non conflictuelle avec le terrain. La reprise en main s'effectue sur décision du pilote. Le déclenchement peut-être limité à un volume aérien donné (une altitude seuil par exemple); dans ce dernier cas, ils sont moins contraignants pour le pilote.

La force première de ces systèmes de type 1 est leur pragmatisme: il n'exigent aucune théorie de la situation, qu'elle soit bio-médicale (théorie du Gloc) ou tactique (théorie sur la compréhension de scène). Ils sont quasi-opérationnels aux USA et pourraient être rapidement disponibles en France (1992-1995).

<u>Les systèmes de type 2</u> sont des "recovery systems" plus sophistiqués que les précédents essentiellement parcequ'ils sont basés sur une théorie bio-médicale du Gloc. Dans ce cas, le recueil de très peu de paramètres clés bio-médicaux est suffisant au diagnostic; le système est normalement plus efficace que le système de type 1 (à la réserve près de la qualité d'extraction du ou des signaux biologiques); ils peuvent être à déclenchement complètement automatique (évitant ainsi les dialogues de confirmation) mais ils restent des systèmes temps de paix puisqu'ils sont démunis de modèles tactiques. Des systèmes hybrides entre le type 1 et le type 2 (utilisation d'indices bio-médicaux sur des hypothèses théoriques, couplés à des indices pragmatiques de type contextuels) pourraient être en service assez rapidement mais ils n'ont pas encore fait la preuve qu'ils étaient meilleurs que des systèmes plus simples de type 1. Des systèmes de type 2 complètement automatiques ne devraient pas être disponibles avant 2000-2005.

<u>Les systèmes de type 3</u> sont des systèmes temps de guerre destinés à suppléer aux pertes de connaissances pilotes; ils comportent un module de diagnostic de la perte de connaissance et de la reprise de conscience provoquant moins de faux-positifs que les systèmes de type 2. Ils sont couplés à un gestionnaire tactique de la trajectoire (partie du copilote électronique) qui ne fait pas partie du filet de sauvegarde au sens propre mais qui en dirige l'usage. Ils doivent donc être basés sur une théorie de la situation (qui peut se limiter aux aspects tactiques; les aspects de diagnostic de perte de conscience peuvent être réglés sur le même mode semi-automatique que les systèmes de type 1). Ils ne devraient pas être disponibles avant 2005-2010.

<u>Les systèmes de type 4</u> sont des systèmes temps de guerre destinés à parer aux menaces immédiates en respectant l'enveloppe physiologique du pilote, mais allant éventuellement jusqu'au risque de perte de conscience. Ils comportent un modèle de

l'enveloppe physiologique du pilote, un système de test de reprise de conscience et un gestionnaire tactique de la trajectoire. Ils pourraient être disponibles pour la génération d'avions à venir : l'EFA Anglais, l'ATC Américain et peut-être l'ACF Français (2005-2010).

Enfin, les systèmes de type 5 seraient des systèmes capables de prévenir les pertes de connaissance; bien que ces systèmes paraissent déjà peu réalistes pour des raisons purement techniques (absence de modèles théoriques des prémices de la perte de conscience), ils posent une autre question qui tient à leur interêt stratégique : les pilotes opérationnels accepteront-ils de se priver du domaine de vol atteint avec la perte de connaissance?

On constate à l'examen de ces systèmes une évidente hiérarchie de complexité qui se retrouve dans les délais de mise en service. La logique voudrait que l'on implémente très vite les systèmes les plus simples. Mais cette évolution par paliers successifs, temps de paix, puis temps de guerre, n'est pas sans poser questions sur l'usage que pourront en faire les pilotes : les pilotes habitués à ces sytèmes auront peut-être du mal à s'en passer, les prises de risques seront peut-être excessives en l'absence du système...ou inversement; la philosophie d'emploi opérationnelle reste complètement à définir en ce domaine; l'article de **Mc Bride & al** (même ouvrage) introduit ce type de discussion.

3-Discussion sur les aspects psycho-physiologiques

Il y a quelques années dans les congrès de médecine aérospatiale, un des thèmes essentiels était celui des pertes de connaissances brutales en vol liées aux accélérations de haut niveau et engendrant des accidents avec perte d'avions et de pilotes. Les différentes nations possédant de tels avions présentaient leurs statistiques et essayaient de dégager des mesures de prévention (**Johanson & Pheeny, 1988**). Certains facteurs comme l'âge, le poids, la taille ne semblent pas déterminants. Par contre l'efficacité des protection antiG et l'entrainement physique des pilotes paraissent essentiels.

A l'heure actuelle les GLOC sont toujours évoquées dans les congrès mais c'est beaucoup plus pour discuter les mécanismes physiologiques liés de leur déclenchement, et discuter les moyens de les prévenir. Le débat s'est dépassionné, des travaux minutieux doivent être menés pour mieux connaitre ces phénomènes. De nombreux laboratoires de recherches dans le monde travaillent en profondeur sur ce sujet.

3-1 Particularités des Gloc:

De nombreuses publications ont présenté la description et les particularités des GLOC. Nous ne ferons que reprendre rapidement les points essentiels qui peuvent être dégagés de l'ensemble de la littérature (**Mc Naughton & Gillighan, 1983, Burton, 1988**).

-Le nombre de GLOC augmente tous les ans du fait de l'accroissement des possibilités techniques des avions dans le domaine de leurs évolutions rapides. Les GLOC tuent, non seulement pour les avions à hautes performances, mais aussi pour des avions plus humbles mais dans lesquels les pilotes ne sont pas équipés de protection antiG.

-La marge entre l'apparition de signes visuels et la perte de conscience est vraiment très étroite. Avec des mises en accélérations rapides, la perte de connaissance peut apparaitre sans prodrome, en particulier visuels.

-La perte de connaissance peut durer longtemps (10 à 20 secondes).

-L'amnésie de cet événement est la règle.

-Certaines pertes de connaissances peuvent être prévenues par un entrainement, une préparation et un équipement approprié. De nombreuses mesures ont été prises dans ce domaine. Nous les mentionnerons ultérieurement.

Il y a toutefois un point qui n'est pas bien connu et souvent mal exploré, c'est la période d'incapacitation. Nous reprendrons la description qu'en a fait **Whinnery & al (1987)**. L'incapacitation totale est la somme d'une incapacitation absolue où le sujet a complètement perdu conscience et d'une incapacitation relative où il reprend progressivement conscience (mais il éprouve des difficultés pour réaliser des traitements d'informations sophistiqués comme on en rencontre couramment dans la tâche de pilotage). Cette période d'incapacitation relative a été étudiée par **Houghton et al (1985)**, **Forster & Whinnery (1988)**, **Whinnery &al (1989)** sur le plan de la performance. Des tâches comportant des mesures de temps de réaction, de résolution de problème et de tracking ont été réalisées en centrifugeuse sur un petit nombre de sujets. Pour toutes les tâches complexes excepté le tracking les performances sont moins bonnes dans la minute qui suit la perte de connaissance. **Houghton** considère aussi que la normalisation de ces tâches secondaires nécessite de 2 à 3 minutes en fonction des sujets. C'est ce temps qui semble le plus réaliste à prendre en compte dans le cas d'une tâche complexe comme le pilotage d'un avion.

3-2 Théories sur leurs apparitions:

L'étiologie hypoxique de la perte de connaissance induite par les accélérations est admise par l'ensemble des spécialistes de médecine aéronautique mondiaux (**Borredon (1987)**, **Clère & al (1987)**, **Burton (1988)**, **Whinnery (1988)**). Quand l'intensité des accélérations centripètes est suffisamment grande et leur vitesse d'application suffisamment lente, le sang a tendance à s'évacuer dans la partie basse du corps. Cette explication des modifications de la perfusion cérébrale a trouvé de nombreuses preuves expérimentales. La plupart des méthodes d'exploration s'attache à suivre des paramétres physiologiques impliqués dans cette théorie. Les mesures de protection et de prévention des pertes de connaissance liées aux accélérations sont aussi dérivées directement de celle-ci.

Mais les pertes de connaissance en vol des pilotes subissant des accélérations de forte intensité et de jolts élevés, sont au plan clinique différentes des pertes de connaissance provoquées par des accélérations plus lentement établies (faible jolt). **Quandieu (1989)**, considérant que les forces engendrées par ce type d'agression sont des forces de volume et non des forces de surface, propose une explication purement physique de ces pertes de connaissance sous jolt élevé. Par augmentation des contraintes mécaniques intratissulaires, une hypertension intracranienne peut se produire. Cette hypothèse est en cours de validation. Si elle s'avérait confirmée, celà aurait pour conséquence de remettre directement en cause les méthodes de protection utilisées jusqu'alors.

3-3 Méthodes d'exploration:

La démarche expérimentale pour valider ces théories porte sur le recueil d'un ou plusieurs paramètres physiologiques en relation avec les théories évoquées précédemment.

Ainsi de nombreuses méthodes d'exploration cardio vasculaire non invasives et invasives ont été utilisées pour valider les hypothèses. On citera , sans être exhaustif, les enregistrements de rithme cardiaque, les mesures de pression arterielle. D'autres paramètres prennent en compte la perfusion cérébrale: citons la mesure de la vitesse d'écoulement sanguin au niveau carotidien, temporal ou de l'artère cérébrale moyenne.

Parmi les méthodes lourdes, citons **Glaister (1988)** qui emploie un détecteur de l'oxygène intracellulaire in vivo en utilisant 4 longueurs d'ondes dans le proche infrarouge (OMNI-4). Cet appareil est capable de mesurer au niveau du cerveau, les quantités relatives d'hémoglobine, d'oxyhémoglobine, de volume sanguin et l'état oxydatif de la cytochrome-c-oxydase. Cet appareillage fonctionne en centrifugeuse. Se posent des problèmes d'industrialisation et d'"avionabilité".

Whinnery & al (1987) ont analysé les différentes techniques de détection de perte de connaissance. La vélocimétrie paraît être une méthode intéressante d'autant qu'elle permettrait de détecter l'imminence d'une perte de connaissance. Les résultats rapportés en France par **Ossard & al (1990)** utilisant le Doppler transcranien ne sont toutefois pas aussi convaincant.

3-4 Mesures actuelles prises pour éviter les Gloc:

Pour l'instant ces mesures sont toutes orientées par la théorie cardio vasculaire. Il faut éviter le stockage sanguin périphérique afin de faciliter la perfusion cérébrale et éviter ces épisodes d'hypoxie cérébrale. Par conséquent les moyens suivants sont utilisés:

- Siège incliné
- Manoeuvres de contraction des muscles abdominaux (type M1)
- Pantalon antiG et amélioration des lois de gonflage avec éventue" ment anticipation
- Respiration en surpression.
- Entrainement physique général
- Entrainement en centrifugeuse

Ces mesures, si elles s'avérent d'une efficacité variable, ne sont que des mesures à priori préventives. Elles doivent permettre théoriquement en jouant sur les facteurs physiologiques réputés en cause de diminuer l'occurence des Gloc. Elles ne permettent en aucun cas de diagnostiquer en temps réel l'état de conscience du pilote.

3-5 outils de mesures physiologiques utilisables en vol, et donc potentiellement intégrables à un filet de sauvegarde

Les outils de mesure de paramètres physiologique utilisables dans le cadre du filet de sauvegarde doivent satisfaire plusieurs contraintes: contrainte de qualité et de stabilité du signal sous facteurs de charge, contrainte d'équipement , de confort et de sécurité pilote, et compatible avec des analyse temps réel (problème d'échantillonage et de traitement).

Là encore, comme pour le paragraphe précédent, à l'heure actuelle les paramétres à prendre en compte appartiennent pour beaucoup au système cardiovasculaire.

Le plus facile à enregistrer est sûrement l'électrocardiogramme, même dans des conditions de vol extrèmes (Quandieu & al. 1988). Ce seul facteur est toutefois insuffisant pour établir un diagnostic de Gloc. Il en est de même des différents recueils electrophysiologiques (EMG, EOG...).

Le doppler transcranien intégré au casque du pilote, évaluant l'irrigation sanguine cérébrale a également été proposé. Il est utilisé en centrifugeuse et il est déjà "avioné" aux Etats-Unis. Mesure prometteuse, mais la qualité , la stabilité du signal et la contrainte pour le pilote sont encore à améliorer.

Le rythme respiratoire est facile à recueillir, mais comme l'ECG, difficile à corréler au Gloc.

D'autres éléments comme la pression sur les commandes sont des paramétres communément suivis en centrifugeuse; la variabilité des résultats ne permet pas une utilisation simple de cet élément.

La voix est enregistrée systématiquement mais non analysée en ligne. Il semblerait que certains composants (formans) soient de bons indices pour estimer la qualité de la reprise de conscience.

Pour un pilote équipé d'un dispositif d'un visuel de casque avec détermination de la position de la tête, la position de la tête pourrait également être un facteur bien corrélé au Gloc mais il manque l'existence d'une base de données : en dehors de quelques travaux menés en centrifugeuse, aucune étude ne peut faire état des "enveloppes" de mouvements de tête dans les vols réels impliquant des phases de vol susceptibles de produire des Gloc. Enfin, à l'avenir, en plus de la détection des mouvements de tête, le couplage de l'oculométrie permettrait non seulement de connaitre la direction du regard du pilote mais également l'état de son système visuel (fermeture temporaire des yeux). Dans ces derniers cas tout un champ d'études est à entreprendre. De tels critères sont peut-être très intéressants mais l'état des recherches est soit confidentiel, soit absent.

Dans tous les cas, nous en sommes encore au niveau de la faisabilité de la prise en compte de certains paramétres spécifiques du pilote. Il ne s'agit pas d'une fin en soi, ni du filet de sauvegarde lui-même. Une base de données et l'établissement des références doivent être établis. C'est seulement à partir de là que l'on pourra envisager l'étape suivante permettant d'effectuer un diagnostic de l'état de conscience du pilote.

4-Discussion sur les aspects informatiques

L'architecture informatique doit répondre à trois types de questions : diagnostiquer la perte de connaissance, diagnostiquer la reprise de conscience et rendre les commandes dans de bonnes conditions, et enfin donner des informations sur l'enveloppe physiologique humaine au module chargé de la trajectoire.

Il doit par ailleurs, dès lors qu'il s'agit de gérer tactiquement la trajectoire (applications temps de guerre), être connecté à des fonctions supérieures de l'appareil : gestionnaire tactique, système de contre-mesures, etc, qui peuvent être centralisées dans un copilote électronique ou distribuées dans un réseau de modules spécialisés (figure 1).

Le choix de l'architecture informatique sera dépendant (i) de la définition de la liste des paramètres à prendre en compte : indices psycho-physiologiques, variables de l'environnement, etc; (ii) de la manière de résoudre le problème de la décision sur la prise autoritaire des commandes.

(i) Sur un plan formel, compte tenu de l'incertitude assez forte de chacun des paramètres pouvant être pris en compte, qu'ils soient contextuels, comportementaux ou psycho- physiologiques, il sera nécessaire de recouper les informations entre elles et de considérer plusieurs paramètres, mais pas trop pour ne pas ralentir les performances. Dès lors trois types de critères peuvent permettre de trier les paramètres retenus dans le système opérationnel: leur pertinence en regard de la perte ou de la reprise de conscience, leur simplicité d'acquisition (minimiser les capteurs biologiques), et leur fiabilité. Les paramètres de contextes permettront de toutes façons de réduire le domaine de surveillance en éliminant les contextes où le risque de Gloc est très faible (croisière, nav TBA, etc) ; la mise en mode combat pourrait être l'argument déclenchant.

Rappelons ici que les systèmes de type 1 représentent un cas particulier et très simple de solution d'architecture du filet de sauvegarde. Ces systèmes semi-automatiques sont en effet basés sur une grande pragmatique du domaine, ne nécessitant pas de théorie pour choisir les paramètres,; ils sont très imparfaits mais pondèrent leurs insuffisances en utilisant un dialogue de confirmation systématique avec le pilote. De tels systèmes peuvent être utilisés sans gestionnaire tactique (simple remise à plat) ou couplés à un gestionnaire tactique (et dans ce cas applicables au temps de guerre).

(ii) La meilleure architecture informatique serait celle qui minimiserait les situations d'indécisions. Une telle architecture devrait alors être nécessairement basé sur l'analyse d'un nombre très limité de paramètres, idéalement un, parfaitement correlé aux Gloc; on peut penser que de telles mesures existeront le jour où les scientifiques possèderont une théorie homogène du Gloc et des mesures à la hauteur de cette théorie.

D'ici là, le problème de l'indécision est bien le problème majeur à résoudre. Deux stratégies peuvent être envisagées: l'approche statistique et l'approche IA.

Dans le premier cas, le système est basé sur des analyses multi factorielles; on recherche les corrélations entre un ensemble de valeurs disponibles et des groupements de valeurs déjà rencontrées dans des Gloc ("patterns") et mémorisés dans le système. Si une identification suffisante est obtenue, le système reprend autoritairement les commandes. Cette solution est simple à mettre en oeuvre mais suppose l'existence d'une base de données (patterns) fiables et représentatifs; or cette base est difficile à obtenir puisque sa richesse tient à l'expérience de situations réelles (évidemment limitée en matière de Gloc).

Il s'agit là d'un véritable problème méthodologique de fond qui est propre à toute démarche empiriste dans le domaine qu'elle soit statistique ou IA: on peut recueillir des dizaines de paramètres en centrifugeuse lors de Gloc provoqués mais les variables comportementales (e.g. position de la tête, pression sur les commandes, reflexes de réponses à des stimulations) ne prennent jamais les mêmes valeurs que dans le réel car il n'y a pas de tâche à effectuer-et pas d'enjeu réel; une base de données constituée en centrifugeuse est donc extrèmement approximative et probablement insuffisante pour une approche statistique aboutissant à une décision aussi grave que la reprise en main autoritaire des commandes. La solution d'une centrifugeuse pilotable par le pilote avec univers de travail réaliste (du type de celle du NADC-Warminster) est sans doute plus valable. Mais c'est la solution du vol réel qui parait de loin la plus efficace, non pas pour recueillir des données sur la perte de connaissance, mais pour recueillir le volume de variations normales des paramètres à surveiller (e.g: enveloppe des mouvements en combat, mais aussi variation du doppler, etc). Dans la mesure où aucun paramètre n'est décisif en lui-même, situer qu'il est dans un domaine anormal constitue une information essentielle pour le système.

En bref il convient de faire une distinction fondamentale entre

-l'obtention de données expérimentales qui valideraient une théorie précise du Gloc ou qui valideraient des outils de mesures (capteurs divers, etc); il s'agit alors de recherches psycho-physiologiques et la centrifugeuse est sans doute un outil essentiel .

-la constitution d'une base de données pragmatiques en rapport avec la présence ou l'absence de Gloc qui servirait un système concret de filet de sauvegarde; dans ce cas la meilleure base de données sera issue du vol réel et construite sur les enveloppes physiologiques et comportementales normales de pilotes observées lors de situations de combat;

L'alternative à l'approche statistique consiste à envisager une architecture IA (Blackboard?) susceptible de raisonner sur les divers paramètres avec un système de règles de décision. Ce type d'architecture est sûrement plus robuste pour faire face à des éventuelles imprécisions de la base de données; les règles risquent cependant d'être difficiles à écrire et l'application temps réel peut poser problème.

5-Conclusion

Le filet de sauvegarde est un concept récent apparu en réponse à la survenue de Gloc sur les avions de nouvelles technologies. Il s'agit d'une réponse pragmatique à la perte de contrôle par le pilote de la situation et non d'une explication de la cause de cette perte de contrôle (mais cette dernière peut évdimment faciliter l'établissement de la réponse). Compte tenu de l'ambiguité filet de sauvegarde-Gloc, la plupart des publications portent sur les mécanismes des Gloc et non sur des systèmes de sauvegarde; elles sont de nature médicales, or la technologie des systèmes de sauvegarde relève plutôt du champ de l'ingénieur, implique des savoirs-faires à protéger, et se retrouve peu dans les publications. C'est précisément une des raisons essentielles qui ont présidé à l'organisation de cette rencontre scientifique pour que des échanges puissent avoir lieu entre les différentes communautés scientifiques et qu'une discussion puisse s'instaurer directement avec ds usager pour mieux définir le besoin immédiat et futur..

Dans tous les cas, le système de sauvegarde doit être le plus efficace possible pour le moins de contraintes sur l'usager. Sur un plan opérationnel, un filet de sauvegarde utilisable en temps de guerre doit être nécessairement lié au copilote électronique; à ce jour, on ne dispose ni de l'un, ni de l'autre. Par conséquent, soit on envisage un système temps de paix rapidement disponible limité au diagnostic de perte de connaissance, soit on remet à long terme le projet d'un filet de sauvegarde qui puisse être utilisé temps de guerre; deux interrogations découlent de ce constat: est-il pertinent d'entrainer les pilotes sur un système dont il ne disposeront plus en temps de guerre, est-il envisageable de se contenter d'un système très simple?.

En France, l'état-major de l'Armée de l'Air s'est engagé à fédérer les différents parties impliqués dans la conception d'un filet de sauvegarde pour le prochain ACF (opérationnels, avionneurs, équipementiers, informaticiens, ergonomes, médecins...). La prise en compte immediate de l'ensemble du problème (y compris le temps de guerre) devrait permettre d'aboutir raisonnablement vite à la conception d'un système réellement utile-et utilisable- pour les pilotes .

REFERENCES:

Borredon P. (1987) Les accelerations +Gz soutenues de haut niveau : impact cardiovasculaire-aspects physiologiques. Med. Aero. Spatiale, XXVI, 101, 19-16

Burton R. (1988) G-induced loss of consciousness: definition, history, current status, Aviat. Space & Env. Medicine, 59:2-5

Clère J.M., Marotte H., Florence G. Vieillefond H. (1987) Pertes de connaissances sous facteur de charge, Med.

Aero. Spatiale, XXVI, 103, 197-201

Forster E., Whinnery J.(1988): Recovery from Gz-Induced Loss of Consciousness: Psychophysiologic Considerations. Aviat. Space & Env. Medicine., 59: 517-522

Gillingham K.(1988) G loss of consciousness, conference EASSA-CERMA Paris, 22.06.88.

Glaister D.(1988): Current and Emerging Technology in G-LOC Detection: Noninvasive Monitoring of Cerebral Microcirculation Using Near Infrared. Aviat. Space & Env. Medicine., 59: 23-28

Houghton J., Mc Bride D., Hannah K.(1985): Performance and Physiological Effects of Acceleration-Indiced (+GZ) Loss of Consciousness; Aviat. Space & Env. Medicine, october 1985, 55: 956-965

Kuipers A. Kappers A. Van Holten C. Van Bergen J. Oosterveld W.(1989) RNLAF Disorientation survey 1988, Proceeding AGARD AMP "Spatial disorientation", Copenhaguen, Oct 1989.

Johanson D., Pheeny H. (1988): A New Look at the Loss of Consciousness Experience Witih the U.S.Naval Forces; Aviat. Space & Env. Medicine, 1988, 59: 6-8

Mc Naughton G., Gillingham K.(1983): G-Induced Loss of Consciousness. Flying Safety, April 1983, 23-27

Mc Bride D. Eddy D. Portillo R. (1990) Navy aircrew opinion of pilot monitoring and recovery systes, AGARD APM safety net meeting, Tours, 2 avril

Ossard G., Clère J-M., Lejeune D., Roncin A., Leger A., Vieillefond H. (à paraitre): Interêt et limites du Doppler transcranien chez des pilotes soumis au facteur de charge, Méd. Aéro & Spatiale, 1990, (à paraitre)

Quandieu P.(1989): Gz et Hypoxie! $Gz.s^{-1}$ et hypertension intracranienne? Méd. aéro. & et Spatiale, 1989, XXVIII, 111, 190-194

Quandieu P., Caillier B., Piedecocq B, Seigneuric A., Pellieux L., Tran C.C., Liebaert P., Lestrade B., Servens E. (1989): Analyse en temps réel de la fréquence cardiaque enregistrée en voi chez des pilotes des chasse soumis à des accélérations +Gz. Rapport CERMA n°89-27 (LCBA).

Whinnery J., Burton R., Boll P., Eddy D.(1987): Characterization of the resulting Incapacitation Following Unexpected +GZ-Induced Loss of Consciousness. Aviat. Space & Env. Medicine, 58:631-636

Whinnery J., Glaister D., Burton R.(1987): +Gz -induced loss of consciousness and aircraft recovery. Aviat. Space & Env. Medicine, 58: 600-603

Whinnery J., Fisher J., Shapiro N.(1989): Recovery to +Gz and +2Gz Following +Gz-Induced loss of Consciousness Operational Considerations, 60: 1090-1095

Whinnery J., Jones D.(1987): Recurrent +GZ-Induced Loss of consciousness. Aviat. Space & Env. Medicine, 1987, 58: 943-947.

Whinnery J.(1988) Converging research on +Gz induced loss of consciousness, Aviat. Space & Env. Medicine, 59, 9-1

Whitley P. (1990) Respiratory function indicators of G induced los of consciousness, AGARD AMP meeting safety net, Tours, 2 avril..

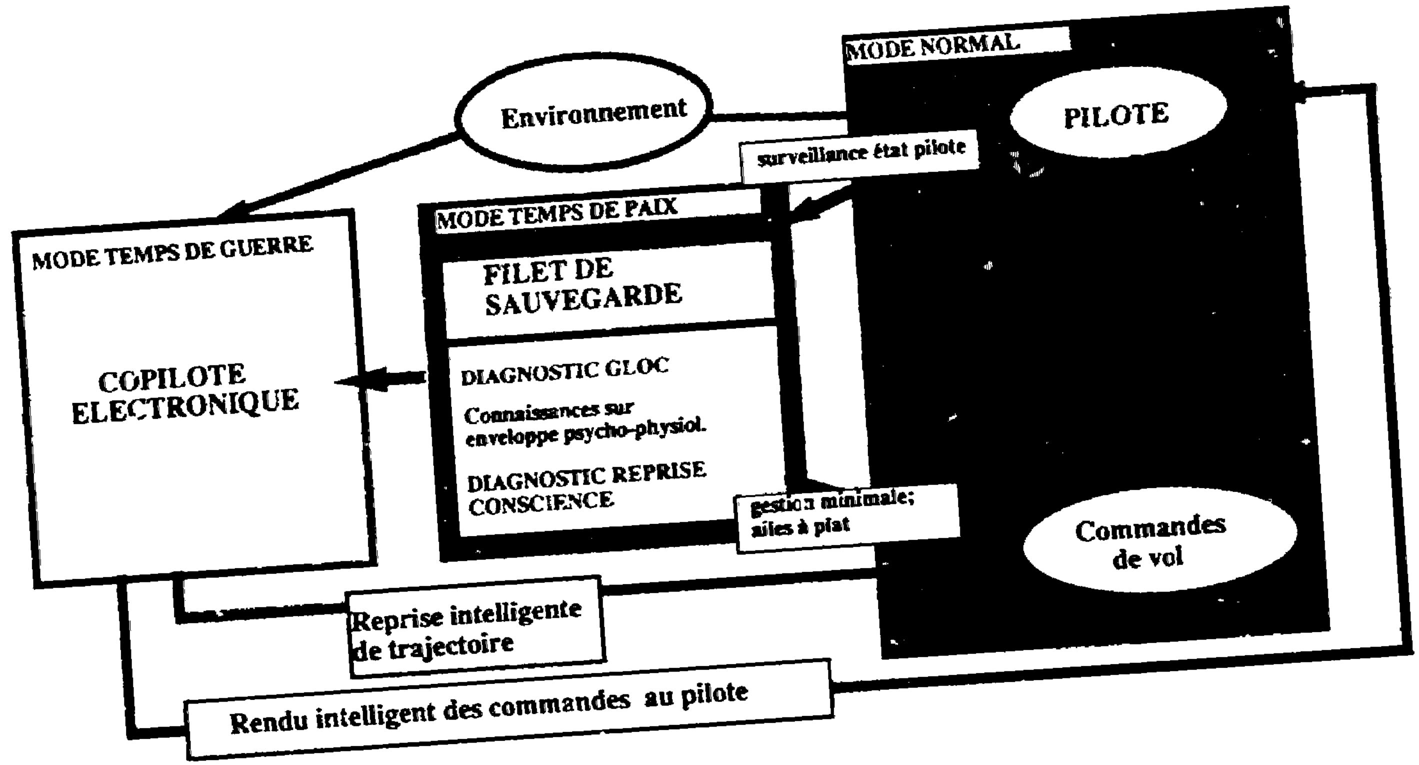

Figure 1 : Architecture temps de paix et temps de guerre du filet de sauvegarde

CEREBRAL OXYGEN STATUS AND G-INDUCED LOSS OF CONSCIOUSNESS

by

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Summary G-induced loss of consciousness (G-LOC) is a common event and has led to the loss of many aircraft and aircrew. While most body systems are ultimately affected, the final common path for its initiation is an inadequate supply of oxygen to the brain. Thus, a measure of cerebral oxygen sufficiency could provide a specific monitor for incipient G-LOC and serve either as a warning to the pilot or as a trigger for an autorecovery system. Multiwavelength near-infrared spectrophotometry permits the non-invasive *in vivo* measurement of the oxygen content of blood within the cerebral microcirculation, and also of the oxygen status of cytochrome-c oxidase within the brain cells. This technique has been validated in human subjects during exposure to hypoxia; in presyncope induced by lower body negative pressure; and during $+G_z$ induced loss of consciousness. It is considered that, as well as providing an important new tool for acceleration research, the technique has the potential to be developed into an in-flight monitor for aircrew.

Based upon several surveys of aircrew populations, G-induced loss of consciousness, or G-LOC, has an incidence of some 12-30% (1-3). The figures vary depending upon aircrew experience (common during training); aircraft type (more common on aircraft with a high sustained G capability); the use and reliability of anti-G equipment (many training aircraft are not fitted with an anti-G system, yet are capable of pulling $+5$-$6G_z$, whilst inadvertent disconnection of the NATO standard anti-G suit connector is not unknown); the accuracy of reporting (centrifuge G-LOC subjects are often unaware of their G-LOC episode and the same may be true in flight); the G-onset rate; and a host of other factors. However, the overall finding is that one in five aircrew will have experienced at least one episode of in-flight loss of consciousness due to $+G_z$ acceleration during their flying career. It is not surprising, therefore, that losses of aircraft and aircrew attributable to G-LOC are reputedly into double figures in the US alone, though to date, no comprehensive survey of accident statistics specifically related to G-LOC has been published.

While recent improvements in G-protective systems, particularly the combination of extended coverage anti-G trousers and pressure breathing (PBG) have produced a dramatic increase in tolerance such that aircrew can be expected to sustain at least $+8G_z$ without the need to perform an anti-G straining manoeuvre (AGSM) (4), the $+9G_z$ capability of the current generation of agile aircraft means that some voluntary effort will still be required even when these new systems become operational. There will, therefore, remain situations in which G-LOC will be an operational possibility, either because of failure to perform an effective AGSM, or through the failure to perceive its need with a rapid onset of acceleration, under which condition G-LOC may occur without the premonitory warning of visual symptoms. Furthermore, no anti-G system can be made 100% reliable and future aircraft can be expected to exceed comfortably the $+9G_z$ performance of current aircraft. Undoubtably, G-LOC will remain a potential problem for as long as men fly agile aircraft whilst seated in such a posture that a significant component of the G force is directed along the $+G_z$ axis of the body.

If the possibility of G-LOC cannot be precluded, then the consequent risk of aircraft loss and aircrew fatality can still be avoided if the G-LOC can be detected in time to initiate an automatic recovery system (5). One possibility is to monitor the performance of the pilot in order to detect, as soon as possible, some reliable indication of a G-LOC. Such a system could monitor the pilot's intelligent use of the controls, or even make use of EEG analysis. A major disadvantage of this approach is that the G-LOC must be allowed to develop before any corrective action can be taken. Even if the autorecovery were effective, the pilot's ability to fight would be denied to him at the very time that it was most needed and his chances of surviving a combat engagement would be close to zero. For application to the training role, though, this approach has the merit of simplicity in that it could make use of state-of-the-art technology, most of which already exists in a combat aircraft's control computers. Figure 1 shows the logic for a proposed system which monitors three inputs - aircraft acceleration, the position of the pilot's head (up or down), and his grip on the stick.

G level		Head position		Hand grip	Action
$<+3G_z$	and	Up or down		Tense or slack	Nil
$>+3G_z$	and	Down	or	Slack	Interrogation
$>+5G_z$	and	Down	and	Slack	Autorecovery

Fig. 1. Operation of a three sensor G-LOC detector system.

Thus, if the aircraft remains below $+3G_z$, no action is taken whatever the pilot is doing, while at greater G levels he will be interrogated should he nod his head, or slacken the grip of his hand on the stick. Failing a positive response, G-LOC would be assumed and the aircraft recovered automatically. Since interrogation takes further time, a third mode of immediate initiation of recovery would operate above $+5G_z$ when the head nods and the hand becomes slack simultaneously. To reduce the incidence of inadvertent operation, the

G sensor would review the recent aircraft history of G exposure and apply a suitable algorithm based upon a conservative G/time tolerance curve.

A more rewarding approach to the problem of G-LOC in flight is to monitor the pilot in such a way that incipient loss of consciousness is detected and a warning given such that he can remain in control, albeit at a voluntarily reduced level of $+G_z$. This is a far harder problem because, despite the vast literature, little is known about the precise mechanism of G-LOC - other than that, in general, it follows a period of inadequate blood supply to the brain with a resulting deficiency in oxygen supply to cerebral tissue.

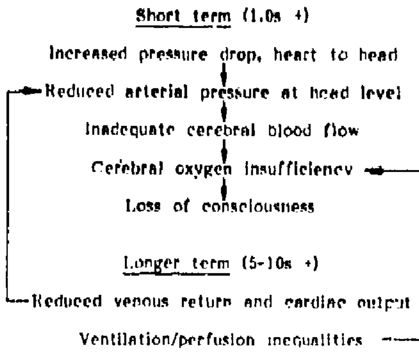

Fig. 2. The basic mechanism of G-LOC.

This mechanism is summarised in Figure 2, from which it may be seen that the G-induced hydrostatic pressure gradient causes a fall in blood pressure, and consequently in blood flow, at the level of the head. In the longer term this fall is exacerbated by a decreased output of blood and pressure at heart level, while the ensuing oxygen insufficiency is further exacerbated by a decrease in the oxygen content of any arterial blood which does reach the brain caused by G-induced ventilation/perfusion inequalities in the lungs.

Several approaches have been made in order to monitor changes in the circulation more or less related to cerebral perfusion. These have included ear opacity (6) (the pressure or absence of arterial pulsation at brain level); blood pressure at head level (now obtainable non-invasively from a finger (7)); and blood flow in a superficial artery (such as the temporal artery) using Doppler techniques (8). All of these measures have been shown to change during, or preceding G-LOC, but they all also show comparable changes at high levels of $+G_z$ in the absence of G-LOC. This is unsurprising as they are all related in some way to pressure and flow in the external carotid artery, while the brain gets its supply from the internal carotid artery. Cerebral blood flow depends upon specific control mechanisms (for example, excess CO_2 dilates cerebral vessels but reflexly constricts those elsewhere in the body), and unique vascular mechanics. The brain is enclosed in the rigid cranium and blood flow will be modified by changes in intracranial pressure as well as by the venous siphon effect demonstrated by Henry et al as early as 1951 (9). For obvious technical and ethical reasons, little is known about the role of cerebro-spinal fluid (CSF) pressure in controlling cerebral blood flow in man at high $+G_z$. An increase in CSF pressure impedes flow in other experimental situation and a decrease, caused by the hydrostatic pressure gradient down the spinal canal, would be expected to keep the cerebral capillaries and veins open and to enhance flow during exposures to $+G_z$. Gross discrepancies in flow between the two branches of the common carotid artery are, therefore, likely under conditions predisposing to G-LOC.

To be effective in anticipating G-LOC, therefore, a monitoring system must be directed to phenomena related to flow in the internal carotid artery and, ideally, at the final common path to G-LOC, cerebral tissue oxygen sufficiency at the cellular level.

A monitoring system for use on aircrew must not add to pilot workload and, if aircrew are to have confidence in it, its application to autorecovery must be free from false positive, or false negative responses. In addition, the system must be non-invasive, non-cumbersome, compatible with other aircrew equipment and, ideally, the subject should be unaware of its presence. One possibility is the use of transcranial Doppler to monitor blood flow in the middle cerebral artery. This vessel supplies a large area of the cerebral cortex and a critical reduction in flow would be expected to precede a G-LOC by several seconds. However, the positioning of the sensor has to be very precise, probably more so even than that for helmet mounted sights and displays, and though the principle has been demonstrated in centrifuge studies (Marcus; Clère: personal communications), it should be noted that it would fail to detect any component to G-LOC contributed by arterial oxygen desaturation. Another possibility which has been evaluated on the centrifuge and which overcomes this criticism is the use of multiwavelength near-infrared spectrophotometry to monitor the oxygen status of the brain tissue (10).

The production of energy within the brain, and hence the maintenance of brain function and consciousness, is dependent upon a series of chemical reactions in which, basically, glucose is oxidised to produce carbon dioxide and water. The last link in this chain involves the enzyme cytochrome-c oxidase which controls 90% of the brain's oxygen utilisation. In its oxidised state, this enzyme has a weak absorption band in the near-infrared region of the electromagnetic spectrum which disappears upon reduction. Reduced and oxygenated haemoglobins also have specific, and stronger absorption spectra in the near-infrared (Fig 3). While skin, bone and brain tissue are

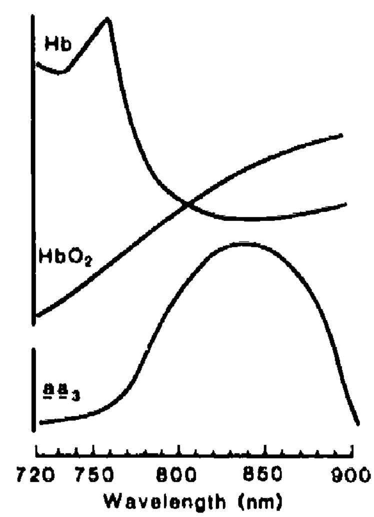

Fig. 3. Near-infrared absorption spectra for haemoglobin (Hb), oxyhaemoglobin (HbO_2) and for oxidised minus reduced cytochrome-c oxidase (a,a_3). (Not to scale).

relatively opaque to light in the visible part of the spectrum, and water present in tissues absorbs photons over most of the infrared region, there is a window in the near-infrared within which some 10% of photons are transmitted per centimetre of tissue. By studying the relative transmission of selected wavelengths of the near-infrared and applying appropriate algorithms, it is, therefore, possible to monitor changes in the tissue concentrations of reduced haemoglobin (Hb), oxy-haemoglobin (HbO_2) and oxidated cytochrome-c oxidase (a,a_3). Furthermore, the sum of Hb and HbO_2 concentrations affords a measure of cerebral blood volume, since the total quantity of haemoglobin in the red blood cells (and, hence in blood) remains effectively constant.

This technique, developed at Duke University Medical Centre and incorporated into and instrument known as OMNI-4 (for Oxidative Metabolism Near-Infrared using 4 Wavelengths) was evaluated at the USAF School of Aerospace Medicine (while the author was an RAF Exchange Officer there) in a series of experiments using hypoxic/hyperoxic breathing gases, lower-body negative pressure (LBNP) and $+G_z$ acceleration.

Figure 4 shows the effect of changing the oxygen content of the gas breathed by a subject seated at rest. With hypoxia (9% O_2 in N_2), the concentration of reduced haemoglobin (Hb) rose, while that of oxy-haemoglobin (HbO_2) fell. Changing to a 95% O_2, 5% CO_2 mixture (the CO_2 being added to maintain cerebral blood flow) caused reciprocal changes in the haemoglobins. Hypoxia also caused a shift in cytochrome oxidase (a,a_3) towards reduction. Cerebral blood volume (BV) remained fairly constant until return to air breathing, whereupon it fell with a coincident reduction in cardiac pulsation - evidence for the pre-existing vasodilation and increased flow invoked by both the hypoxia and hypercapnea.

An energetic Valsalva manoeuvre (Fig. 5) increased cerebral blood volume (CBV), but the increase comprised solely reduced haemoglobin and cytochrome-c oxidase moved towards reduction. This shows the increased volume of venous blood in the brain and reduction in flow produced by a damming up of the brain's venous outflow.

Figure 6 shows average changes in measures of cerebral oxygen status during the last 100 sec of lower body negative pressure exposures which were terminated following symptoms and signs of presyncope. The slight increase in reduced haemoglobin is in striking contrast to falls in oxyhaemoglobin, cerebral blood volume and cytochrome-c oxidase, all of which precede the well documented bradycardia, or cardiovascular decompensation by some 20 s. Presumably, the first sign of failure to compensate for the circulatory stress was a fall in cerebral blood flow and the a,a_3 reduction in particular could have provided an earlier warning of the impending syncope than the generally accepted criterion of a developing bradycardia.

Finally, figure 7 illustrates changes which occurred during a G-LOC induced by exposure to $+5G_z$ with the subject relaxed and unprotected. G-LOC was preceded by a rapid fall in cerebral blood volume, whilst a recovery in blood volume heralded return of consciousness. Unfortunately, the cytochrome-c oxidase signal was not obtained during this run.

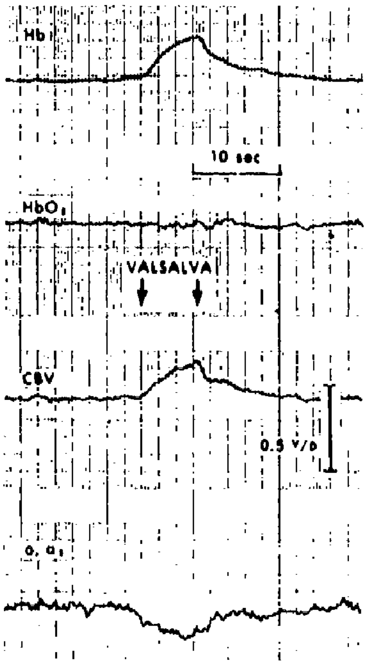

Fig. 5. Effect of a Valsalva manoeuvre at 1G. Recording channels as for figure 4.

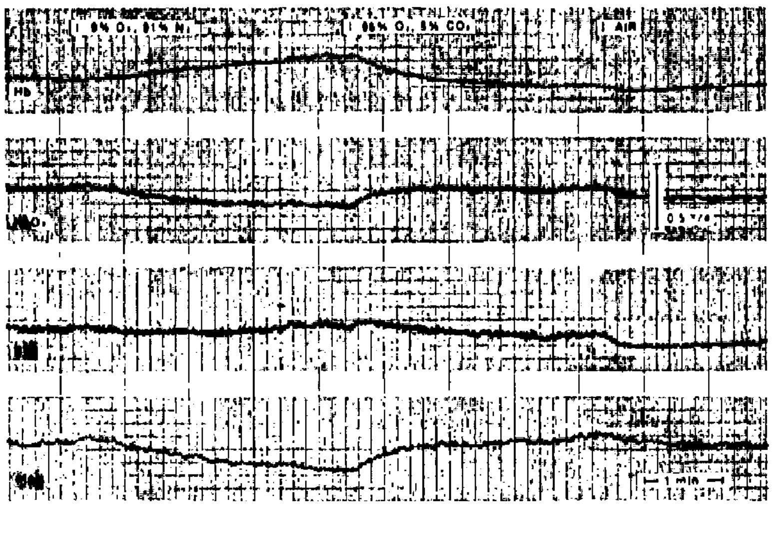

Fig. 4. Response to hyperoxic and hypoxic breathing gas mixtures. The four recording channels are to the same scale (1 $^V/_D$ equals a 10 fold change in tissue concentration) and show changes in haemoglobin (Hb), oxyhaemoglobin (HbO_2), cerebral blood volume (BV) and oxidised cytochrome-c oxidase (a,a_3). The subject was breathing the hyperoxic mixture at the start of the recording.

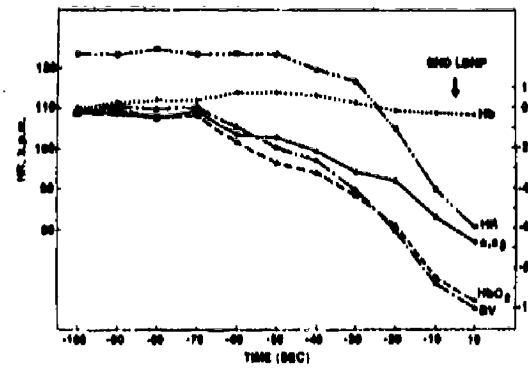

Fig. 6. Changes in heart rate (HR) and in the four OMNI-4 outputs (haemoglobin, Hb; oxyhaemo-globin, HbO_2; cerebral blood volume, BV; and oxidised cytochrome-*c* oxidase, a,a_3). The results are averaged for four subjects over the 100s preceding, and 10s following termination of lower body negative pressure exposures which caused symptoms and signs of presyncope.

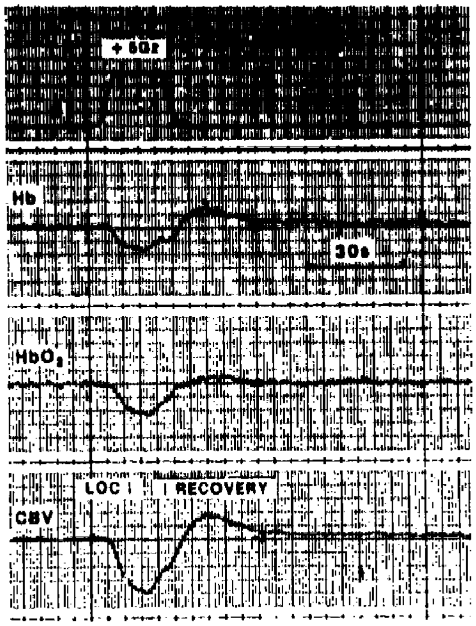

Fig. 7. OMNI-4 outputs during a G-LOC induced by exposure of a relaxed and unprotected subject to $+5G_z$. Full scale deflection for each OMNI-4 channel is equivalent to a 10 fold change in tissue concentration.

From the tests carried out it is clear that the change in haemoglobin concentrations and cerebral blood volume provide a valuable, but still indirect, real time monitor of cerebral oxygen status, but differences between this G-LOC incident and other high G exposures without G-LOC were not great enough to constitute a reliable warning. In theory, changes in cytochrome-c oxidase should prove more reliable, but appeared to suffer from a number of technical problems. Predominant amongst these was the lack of sensitivity in this channel due to its rather weak spectral absorption, and the fact that it could not be detected in its reduced state other than by disappearance of the oxidated cytochrome-c oxidase signal. The use of additional wavelengths and a more sensitive detector should solve these problems. A further problem stemmed from movement artefacts - slight displacement of the optodes through which the near-infrared signals were passed into and received back from the brain led to erroneous signals which could only be overcome by very rigid mounting of a head harness. However, Delpy (personal communication) has suggested that an alternative means for controlling the level of near-infrared energy at the input optode (other than relying on a reflected signal) would eliminate this problem. Thirdly, since the path length through which the signal passes within the brain is unknown, absolute values for concentrations of the chromophores cannot be calculated, only changes. Whilst this is probably not a great disadvantage in a monitoring system, techniques do now exist whereby absolute values could be obtained (11). Finally, the need to carry the signals to and from the head in fairly bulky fibreoptic bundles could be eliminated by the use of lightweight, helmet mounted, solid state devices.

In conclusion, multiwavelength near-infrared spectrophotometry offers a method for monitoring changes in cerebral oxygen sufficiency at tissue level which appear to correlate well with the changes expected under a number of stress conditions, including $+G_z$ acceleration. However, the methodology needs considerable further development.

References

1. Pluta, J C. LOC Survey. Flying Safety. 1984:25-28.
2. Prior, A R J. RAF experience of G induced loss of consciousness. In Proc. High G and High G Protection - Aeromedical and Operational Aspects. R. Aero. Soc. London. October 1987:16-25.
3. Johanson, D C, Pheenny, H T. A new look at the loss of consciousness experience within the US Naval forces. Aviat. Space Environ. Med. 59; 1988:6-8.
4. Prior, A R J. Centrifuge assessment of the $+G_z$ acceleration protection afforded by full coverage anti-G trousers. Aviat. Space Environ. Med. 60; 1989:504.
5. Whinnery, J E, Glaister, D H, Burton, R R. $+G_z$ induced loss of consciousness and aircraft recovery. Aviat. Space Environ. Med. 58; 1987:600-603.
6. Wood, E H, Lambert, E H. Some factors which influence the protection afforded by pneumatic anti-g suits. J. Aviat. Med. 23; 1952:218-228.
7. Prior, A R J. Physiological aspects of an enhanced G protection system. Proc. 11th Ann. Meeting IUPS Commission on Gravitational Physiology. Lyon, September 1989.
8. Hrebien, L. Current and emerging technology in G-LOC detection : pulse wave delay for $+G_z$ tolerance assessment. Aviat. Space Environ. Med. 59; 1988:29-31.
9. Henry, J P, Gauer, O H, Kety, S S, Kramer, K. Factors maintaining cerebral circulation during gravitational stress. J. Clin. Invest. 30; 1951:292-300.
10. Glaister, D H, Jöbsis VanderVliet, F F. A near-infrared spectrophoto-metric method for studying brain O_2 sufficiency in man during $+G_z$ acceleration. Aviat. Space Environ. Med. 59; 1988:199-207.
11. Delpy, D T, Cope, M, van der Zee, P, Arridge, S, Wray, S, Wyatt, J S. Estimation of optical path length through tissue from direct line of flight measurement. Phys. Med. Biol. 33; 1988:1433-1442.

DETECTION DES PERTES DE CONNAISSANCE EN VOL PAR METHODE DOPPLER

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RESUME: L'utilisation d'un Doppler transcrânien a été préconisé pour détecter la survenue de pertes de connaissance induites par les accélérations. Un appareil de type Doppler pulsé transcrânien a été developpé spécifiquement pour fonctionner en centrifugeuse et un autre pour être installé dans un Mirage 2000, ce qui a impliqué des contraintes supplémentaires pour respecter l'environnement de sécurité imposé par son utilisation en vol. Au cours d'une étude menée pour évaluer la tolérance de 9 sujets soumis à des accélérations à +8 Gz, le Doppler transcrânien a permis de montrer qu'il existait dans 23 cas une relation entre la réduction du signal vélocimétrique de la circulation dans l'artère cérébrale moyenne et la diminution du champ visuel; dans 9 cas, cette relation n'a pas été observée et dans un cas une faible diminution du signal Doppler a été suivie par une perte de connaissance. La détection des pertes de connaissance en vol implique l'utilisation de plusieurs paramètres physiologiques et de paramètres de vol qui devront être analysés avant de déclencher une procédure automatique de sauvegarde de la part de l'ordinateur de bord. Ceci nécessite le développement de procédures nouvelles et complexes. Dans cette attente, le meilleur traitement des pertes de connaissance consiste à se placer dans des conditions préventives optimales grâce aux récents moyens de protection anti-G (siège incliné, respiration en pression positive, pantalon anti-G couvrant complètement la parie inférieure du corps).

1. INTRODUCTION.

L'existence des pertes de connaissance en vol est connue depuis la première guerre mondiale. A ce jour, les pertes de connaissance en vol sont redoutées car elles surviennent la plupart du temps au cours du combat aérien et dans certains cas, elles entraînent non seulement la perte d'un avion, mais surtout celle de l'équipage.

Des études récentes, en particulier celles de PLUTA (1984) et de WHINNERY (1986) ont montré qu'il existait en temps de paix une nette recrudescence de ces phénomènes avec les avions de la classe F 16 ou avec des avions d'entraînement chez des pilotes en cours de formation.

2. COMMENT PREVENIR OU TRAITER LA PERTE DE CONNAISSANCE?

A ce jour, plusieurs solutions sont proposées aux Etats Majors :

- Limiter les performances des avions afin d'éviter qu'ils n'atteignent des accélérations ou des taux de mise en accélération élevés. Ce serait alors le système d'arme (radar, missile très manoeuvrant, contre-mesures électroniques) qui devrait compenser cette réduction de performance. Actuellement, cette solution ne semble pas retenue. Toutefois, une intervention sur les algorythmes des commandes de vol électroniques peut-être réalisée en réduisant légèrement les performances de l'avion sans pénaliser pour autant ses évolutions.

- Augmenter la protection anti-G. C'est le cas pour les Armées de l'Air qui utilisent des avions avec siège incliné et qui pratiquent l'entraînement physique et l'entraînement en centrifugeuse. Ce sera le cas pour celles qui utiliseront la surpression respiratoire. L'augmentation de la tolérance des pilotes aux accélérations reste la solution la plus rationnelle.

- Détecter l'imminence de la perte de connaissance ou son existence. Il s'agit d'une ultime sauvegarde qui semble t-il a pour principal intérêt d'être utilisée en temps de paix. Elle préservera de toute façon la vie de nombreux pilotes. Cette dernière solution peut co-exister avec l'une ou l'autre des solutions précédentes. Mais comment détecter ces pertes de connaissance?

3. DETECTION DES PERTES DE CONNAISSANCE.

Dans le cas où la perte de l'aéronef ou du pilote lors du combat aérien est uniquement liée à une perte de connaissance, il faut mettre au point des systèmes experts capables de détecter la perte de connaissance de façon fiable puis de renseigner l'ordinateur de bord. Celui-ci devrait ensuite effectuer automatiquement une manoeuvre de sauvegarde.

Les paramètres utilisés peuvent être :
- des informations de vol,
- des variables physiologiques.

WHINNERY et Coll. (1987) ont rappelé les principaux paramètres physiologiques utilisables dont la mesure du débit sanguin cérébral.

4. INTERET DU MONITORING DE LA CIRCULATION SANGUINE AU NIVEAU DU CERVEAU.

Deux raisons sont en faveur de cette solution:

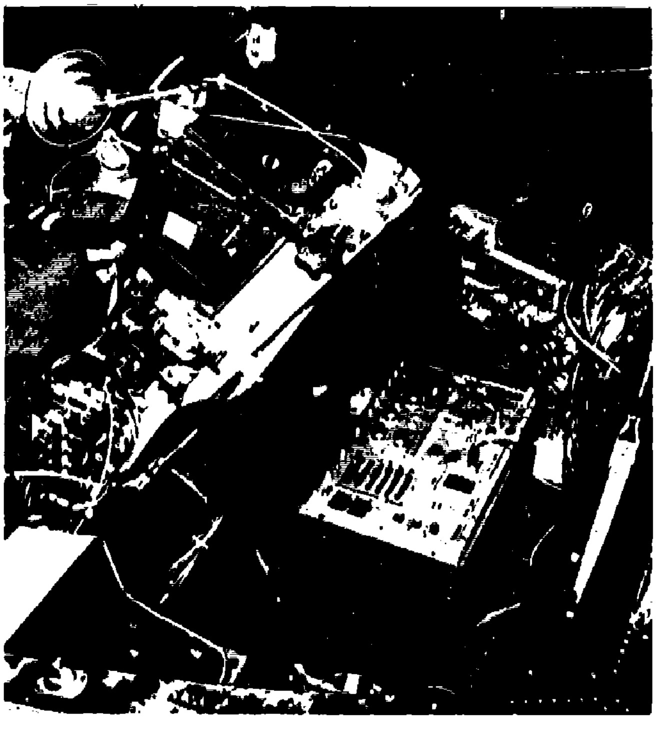
Lors du combat aérien, les accélérations de niveau élevé et rapidement installées peuvent entraîner une réduction ou un arrêt de la circulation sanguine au niveau du cerveau. Il est donc logique de chercher à détecter une éventuelle chute de débit.

Les technologies modernes permettent de disposer de systèmes non invasifs d'évaluation de l'hémodynamique des grands axes vasculaires cérébraux. Le Doppler fait partie de ces moyens. Le système peut-être miniaturisé et facilement installé dans un aéronef.

Ces différentes raisons ont conduit le Laboratoire de Médecine Aérospatiale (LAMAS) à mettre au point un système de ce type. Celui-ci aura non seulement pour intérêt d'appréhender les variations de débit sanguin sous facteur de charge chez l'homme et de détecter l'imminence d'une perte de connaissance mais également d'évaluer la qualité des nouveaux concepts ou des nouvelles technologies de protection anti-G.

5. MATERIEL.

Le LAMAS a bénéficié de l'expérience du Laboratoire de Biophysique Médicale de l'Université F. Rabelais de Tours en matière d'électronique écho-Doppler. Ce laboratoire a développé un système fonctionnant sous fort facteur de charge. Un premier appareil muni de sondes couplées écho-Doppler (photographie n° 1) a permis de faire une étude concernant les variations du débit de la carotide primitive sous accélération (Florence et coll. 1989). La visualisation en image échographique de la carotide et de l'angle de pénétration du faisceau Doppler associé à la mesure de la vitesse d'écoulement a permis de calculer le débit en fonction du niveau d'accélération.



Photographie n° 1: Appareil echoDoppler monté à l'intérieur de la contrifugeuse.

A la suite de cette étude, il a paru intéressant de compléter ce travail par la mesure du débit sanguin au niveau du cerveau. Pour cela une carte électronique spécifique a été installée dans cet ensemble.

Il s'agit d'un Doppler pulsé dont les principales caractéristiques comportent :

- une émission-réception à 2 MHz,
- une fenêtre de mesure de largeur fixe, ajustable en profondeur entre 30 et 100 mm,
- un système permettant de détecter le caractère antéro ou postérograde du flux sanguin,
- un filtre BF de bande passante 5 à 150 KHz,
- une sortie audio analogique.

6. PROTOCOLE.

Une première expérimentation a été effectuée à l'aide de cet appareil au cours de l'évaluation de lois de gonflage de pantalon anti-G (Lejeune et coll. 1990).

Neuf volontaires masculins ont été soumis à trois profils d'accélération à + 8 Gz; deux d'entre eux ont effectué l'expérimentation deux fois car ils ont participé à la mise au point. Ils n'effectuent pas de manoeuvre anti-G mais portent un pantalon anti-G actuellement en service dans l'Armée de l'Air française. Trente trois tracés de signal Doppler ont été recueillis au cours de cette expérimentation.

La loi de gonflage du pantalon anti-G est différente pour chaque profil d'accélération.

La limite de tolérance a été définie comme la perte de 60 pour cent du champ visuel périphérique selon l'axe horizontal.

La mesure de la vitesse d'écoulement du sang est effectuée au niveau de l'artère cérébrale moyenne (ou artère Sylvienne) dont l'abord est aisé (photographie n° 2). Une analyse spectrale de la vitesse sanguine dans la fenêtre de mesure est réalisée grâce à un analyseur de spectre de type Angioscan.

Photographie n° 2: sujet d'expérimentation équipé de la sonde Doppler transcrânien.

7. RESULTATS.

Sur 33 tracés obtenus lors des 33 lancements en centrifugeuse, dans 23 cas il existe une réduction du champ visuel précédée par une diminution du signal Doppler. Dans 9 cas, la diminution ou la disparition du signal Doppler n'est pas suivie par une diminution du champ visuel. Dans ces 9 cas, la disparition du signal doppler s'effectue durant les accélérations élevées et le signal réapparait lors du retour à une gravité normale (1 G). Dans un dernier cas, il y a une perte de connaissance avec une discrète réduction du signal Doppler.

Photographie n° 3: Sujet soumis à une accélération de +8 Gz.

8. DOPPLER EN VOL.

Parallèlement, un appareil Doppler transcrânien utilisable en vol a été développé. Il présente les mêmes caractéristiques que celui décrit auparavant. Il s'agit toutefois d'un ensemble qui doit répondre à des spécifications aéronautiques supplémentaires:

- installation dans un boitier spécifique pouvant être monté à bord d'un avion.
- absence d'interférence avec l'environnement électromagnétique de l'avion de manière à ne perturber ni l'équipement électronique de celui-ci, ni la mesure vélocimétrique sanguine.

L'expérimentation sera effectuée en vol sur un Mirage 2000 spécifiquement adapté aux essais en vol.

Le signal est recueilli sur un enregistreur analogique multipiste installé dans un pod, sous l'avion. L'ensemble peut supporter des accélérations jusqu'à +9 Gz.

L'électronique est installée dans un boitier OTAN 2 U de dimension et de poids réduits; la consommation électrique est faible (5 W.)

En face avant du boitier sont installés :

- le connecteur pour la sonde
- le réglage de la profondeur de la fenêtre
- le connecteur pour l'écouteur utilisé lors de la mise en place de la sonde dans l'avion.

En face arrière sont installés :

- le connecteur d'alimentation
- les deux connecteurs de sortie audio du signal.

Il a fallu développer un support spécifique de sonde à l'intérieur du casque qui permette de positionner celle-ci de façon aisée sans qu'elle soit mobile pour autant. Cet ensemble prend en compte les normes de sécurité appliquées aux avions de combat en cas d'éjection.

Le câble de sonde comporte donc un connecteur à dégrafage rapide installé sur la Mae West.

Les vols vont avoir lieu durant les mois de septembre et octobre 1990. Les pilotes d'essais ou les expérimentateurs auront à se soumettre à des profils d'accélérations dont certains seront reproduits sur la centrifugeuse du laboratoire.

Deux comparaisons pourront être menées :

- une première entre situation de laboratoire en centrifugeuse et situation de vol réelle.
- une deuxième entre pilote situé en place avant et expérimentateur situé en place arrière.

Ces comparaisons permettront de distinguer les effets sur la circulation sanguine cérébrale :

- des accélérations +Gz subies d'une part en centrifugeuse et d'autre part en avion
- des accélérations en vol qu'un pilote anticipe parce qu'il les commande, de celles qui le surprennent parce qu'il est copilote expérimentateur.

Quoi qu'il en soit, les premières données recueillies peuvent se discuter en terme de régulation sanguine cérébrale et en terme de détection des pertes de connaissance, voire en terme de qualité de métrologie.

9. DISCUSSION.

En résumé, nous avons trois situations où :

- la réduction ou l'abolition du signal Doppler est bien suivie d'une réduction du champ visuel; soit une bonne concordance des deux paramètres.
- l'abolition du signal Doppler n'est pas suivie d'une réduction du champ visuel; soit une mauvaise concordance entre ces deux signaux.
- la diminution du signal Doppler est faible et une perte de connaissance survient, ce qui correspond à un seul des cas observés.

Dans le cas où la diminution du débit sanguin précède bien la diminution du champ visuel, on peut penser que la diminution de la pression de perfusion sanguine liée aux accélérations entraîne bien une diminution du débit sanguin cérébral. Cette diminution de débit, on la retrouve à la fois au niveau de la vascularisation rétinienne, mais peut être aussi au niveau de la zone occipitale où se situent les aires visuelles .

La loi de Bernoulli liant pression de perfusion et débit serait respectée. Il y aurait en quelque sorte avec nos vingt-trois cas une triple fonction qui lie:

- accélération et pression de perfusion,
- pression de perfusion et débit,
- débit et champ visuel.

Les relations faites ci-dessus ne prennent pas en compte la pression veineuse de la circulation sanguine de retour qui semble également importante dans la régulation du débit sanguin intracérébral.

Par ailleurs, Kontos et Coll. (1978) ont montré chez le chat anesthésié que la régulation du débit sanguin dans les vaisseaux cérébraux était fonction de leur diamètre. L'abolition du signal Doppler non suivie d'une réduction du champ visuel observée dans neuf cas pourrait être expliquée par un régime vasomoteur spécifique. L'importante réduction du signal Doppler pourrait ne pas correspondre à un arrêt de la circulation cérébrale. Il s'agirait d'un phénomène similaire à celui de la circulation pulmonaire où la pression de perfusion est faible ainsi que la vitesse d'ecoulement mais dont le débit est important. Par cette analogie, Il est licite de penser qu'une oxygénation suffisante des "territoires clés de la conscience" et de la rétine soit obtenue.

Enfin, dans le dernier cas, où apparaît une perte de connaissance avec une réduction du signal Doppler, cette situation a déjà fait l'objet d'une discussion (Clère et coll. 1989) où est rappelée l'affirmation de Werchan (1989) selon laquelle une diminution de 40 pour cent du débit sanguin cérébral peut être suffisante pour faire apparaître des troubles EEG. Cette hypothèse se présente en quelque sorte en opposition avec l'hypothèse précédente.

Ainsi, le signal Doppler parait complexe à analyser. Son abolition n'est pas équivalente à une perte de connaissance pour plusieurs raisons physiologiques mais aussi d'ordre méthodologique et métrologique.

Sur le plan méthodologique, l'artère cérébrale moyenne n'est peut être pas l'artère qu'il faut explorer, même si son abord est relativement aisé.

Sur le plan métrologique aucune certitude n'existe quant à l'immobilité de l'artère et du capteur sous accélération.

L'évaluation du débit sanguin dans l'artère cérébrale moyenne paraît à ce jour insuffisante à elle seule pour détecter l'imminence d'une perte de connaissance. Seul, un système intégrant plusieurs paramètres physiologiques et de vol sera à même de prédire l'imminence ou de détecter la survenue de la perte de connaissance. Ceci ne pourra être mis au point qu'après une expérience comportant des pertes de connaissance observées en centrifugeuse avec des sujets équipés de capteurs. A ce jour, pour des raisons éthiques il est très difficile en France d'effectuer une expérimentation spécifique concernant les pertes de connaissance sous facteur de charge. Seules les pertes de connaissance accidentelles observées au cours d'expérimentations permettront de statuer sur la validité d'un paramètre physiologique, débit cérébral ou autre, et de définir les critères prédictifs d'une perte de connaissance.

10. CONCLUSION.

La détection des pertes de connaissances pourrait être effectuée à l'aide de paramètres physiologiques. Dans cette étude, il est montré qu'elle est basée sur l'utilisation d'un Doppler transcrânien. Il n'existe pas de relation simple entre arrêt du signal Doppler et perte de connaissance. Ces paramètres devront sûrement être multiples et complétés par des données de vol. Une analyse pertinente voire empirique de ces paramètres devrait informer l'ordinateur de bord d'une situation d'état lui permettant d'effectuer une manoeuvre de sauvegarde. La complexité de ce système fait penser qu'il s'agit d'un ensemble qui ne pourra être utilisé que dans un futur relativement lointain.

11. REFERENCES.

J.M. CLERE, D. LEJEUNE, G. OSSARD, A. LEGER, A. RONCIN. G-Loss of consciousness detection limits with transcranial Doppler monitoring. 11th Annual Meeting IUPS, Commission of Gravitational Physiology, 25-27 Sep.1989, Lyon, FRANCE.

G. FLORENCE, J.M. CLERE, H. MAROTTE, A. LEGER. Variations of common carotid flow with +Gz stress measured by echo-Doppler. Aviat. Space Environ. Med. 1989; 60(5):128.

H.A. KONTOS, E.P. WEI, R.M. NAVARI, J.E. LEVASSEUR, W.I. ROSENBLUM , J.L. PATTERSON Jr. Responses of cerebral arteries and arterioles to acute hypotension and hypertension. Am. J. Physiol. 1978; 234(4):H371-H383.

D. LEJEUNE, J.M. CLERE, G. OSSARD, A. LEGER. Does the anti-G inflation anticipation improve G-tolerance? 61th Meet. of Aerospace Med. Association. New Orleans, LA. USA, May 13-17, 1990.

J.C. PLUTA. LOC survey. Flying safety. Jan. 1984:25-8.

M. SPENCER, P. WERCHAN, D. DAVIS, M. McDANIEL, R.R. BURTON. Transcranial Doppler monitoring of middle cerebral artery flow velocities during +Gz accelerations. 1989; 3rd International Symposium and Tutorial on Intracranial Hemodynamics: transcranial Doppler and cerebral blood flow. 13 Feb. 1989, San Antonio, TX. USA.

P.M. WERCHAN. Physiologic bases of G-LOC. 60th Meet. of Aerospace Med. Association. Washington DC. USA, May 7-11, 1989.

J.E. WHINNERY. +Gz-Induced Loss of Consciousness in undergraduate pilot training. Aviat. Space Environ. Med. 1986; 57(10):997-9.

J.E WHINNERY, D.H. GLAISTER, R.R. BURTON. +Gz-induced loss of consciousness and aircraft recovery. Aviat. Space Environ. Med. 1987;58(6):600-3.

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CURRENT STATUS OF AN ARTIFICIAL INTELLIGENCE-BASED LOSS OF CONSCIOUSNESS MONITORING SYSTEM FOR ADVANCED FIGHTER AIRCRAFT

by

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SUMMARY

During this past decade, fourteen U.S. Air Force pilots lost their lives and aircraft to gravity induced loss of consciousness, or GLOC. GLOC is not a new problem, it has been around for over 70 years. Because of the emergence of high performance aircraft such as the F-16 and F-15 and the fact that these aircraft can perform beyond the acceleration tolerance limits of the human, GLOC has become the U.S. Tactical Air Force's second most serious human factors problem, second only to spatial disorientation. To date, there exists no monitoring system in USAF aircraft to detect when a pilot has become incapacitated due to GLOC. The incorporation of high G onset training and a special centrifuge training facility will help reduce, but not eliminate, the GLOC problem. This paper presents the current status of a loss of consciousness detection and recovery system being developed by the Air Force.

PREFACE

There is virtually no cardiovascular, cardiopulmonary or encephalographic physiological variable which cannot be measured in flight. Venous and arterial in-dwelling catheterization with pressure transducers can provide realtime cardiovascular information, and electroencephalography can provide a very precise indication of the loss of consciousness event in realtime as well.

The acquisition of these kinds of data in a two place fighter-class aircraft under carefully controlled in-flight conditions is one thing. Their acquisition and utility in the setting of the operational cockpit is quite another. In the Loss of Consciousness Monitoring System (LOCOMS) effort at the AAMRL the original approach to monitoring was based upon these kinds of metrics. They were, however, abandoned in the face of the stark realities of getting and using such information in the air combat arena.

Subsequently our approach has been that of relying only upon those physiological metrics which might be obtain unobtrusively, which would be essentially transparent to the fighter pilot, and which (ideally) might be reliably obtained without sticking into or onto the aviator (Van Patten, 1986). Our subsequent efforts have concentrated on the following:

a. Eye blink rate.
b. Head slumping.
c. Strength or absence of grip on stick, and spectral content of stick inputs.
d. Head level arterial pulsations.
e. Acceleration-sensitive eye level blood pressure model.
f. Arterial oxygen saturation percentage, presence of pulse pressure.
g. Spectral shift in frequency of Electroencephalogram (EEG).
h. Presence and quality of straining maneuver.
i. Anti-G Suit (AGS) function.
j. Pilot response to voice synthesized interrogation.
k. Potential resuscitation measures.

The sine qua none of any practical LOCOMS will be a low false alarm rate. A system that is constantly querying the pilot as to his status will not find a high level of user acceptance and will be turned off. Consequently it will be necessary to combine evaluation of physiological metrics with evaluation of the past and present status of the aircraft in terms of:

a. Altitude
b. Recent time history of:
   (1) Gz exposure above +4 Gz
   (2) Onset rate of the exposure
   (3) Duration of the exposure
c. As well as:
   (1) Current Gz
   (2) Cumulative G-time maneuvering metric

In our conceptual design philosophy these six maneuver-related metrics would be combined with the eleven physiological metrics with the outputs of these two systems serving as input attributes to an artificial intelligence-based inference engine capable of making decisions based on the data. Sufficient in-house research has been done with such an inference engine to make it clear that this portion of the concept poses no technological problems (Van Patten, 1988). Figure 1 shows some of the interrelationships in this concept.

Before proceeding to a discussion of the status of current research it is necessary to briefly touch upon an issue that is raised frequently by potential operational users. Given the assumption of a practically infallible LOCOMS, what form must recovery of the aircraft take? In the combat setting, recovery of the aircraft to straight and level flight, it is feared, would place the unconscious (but recovering) pilot in the role of easy prey for any attacker.

In their GLOC studies atthe USAF School of Aerospace Medicine, Whinnery (C. Whinnery, et al, 1990) has found that subjects experiencing GLOC recover faster when returned to a higher than 1 G threshold, such as 3 Gz. This finding is good on two counts: 1) the total incapacitation period of the subject, or pilot, can be reduced and, 2) the aircraft in which the GLOC-pilot is a passenger (since he/she surely isn't flying the aircraft, can be placed by a LOCOMS/flight control computer system into a 3 Gz turn or evasive maneuver until the pilot is no longer totally incapacitated.

Although far beyond the expertise of those of us working the physiological side of this problem, it seems plausible that current work on automated maneuvering attack and missile evasion systems could provide relief. In a combat situation in which a recovery is taking place, it seems reasonable to assume that an attacking aircraft or missile would be "painting" the target aircraft with gun or missile guidance radar and that on-board receivers and radars would be capable of detecting the emissions and/or the presence of an attacking aircraft or missile. That being the case pre-programmed evasive maneuvers could be automatically commanded while resuscitation measures were being applied to the pilot. For the moment, we assume that by the time an operational LOCOMS system could be deployed the technology for automated evasive maneuvers will be in hand.

1. CURRENT DEVELOPMENT STATUS

a. Eye Blink Detection

Blink rate is a well known indicator of arousal and is much easier to detect than eye position. In our program a miniaturized device was developed under a Small Business Innovative Research effort (Energy Optics, Las Cruces, NM) which uses infra-red light to illuminate the eye. The device mounts on the oxygen mask out of the line of sight and reacts to the change in reflected light from the area when the lids close (Figure 2). The detector is about the size of the metal ferrule on a common lead pencil and has been shown to be over 90% reliable under sustained acceleration, yielding good results irrespective of skin pigmentation (O'Brien, 1987). Evaluation of a zero blink rate is not without some difficulties. Some (conscious) individuals virtually cease blinking when concentrating intensely under sustained acceleration (Albery, 1989). Consequently a zero blink rate in the presence of an erect head would not be as significant as would a zero blink rate in the presence of a slumped head. These two signs, taken together, would provide a reliable indicator of unconsciousness.

b. Head Slumping

At the onset of loss of consciousness a total body muscular flaccidity takes place. Since the center of gravity of the head/helmet is not aligned with its support (the neck) the head will slump in whatever direction is dictated by the local gravity vector. This phenomenon can be detected by means as simple as three mercury switches to as complicated as the techniques used for measuring head position in helmet mounted sight systems. This information could serve double duty in a LOCOMS. A system developed in our laboratory is shown in Figure 3.

c. Strength or Absence of Grip on Stick

Because of the muscular flaccidity described above, the characteristics of the pilot's grip on the stick will change markedly with the onset of unconsciousness. Many researchers have suggested that this signal should be the easiest and most reliable signal to detect because the GLOC should cause the pilot to release the control stick. This has not been observed in all of the 500 cases videotaped and archived in the USAF School of Aerospace Medicine library, however. More precisely, one needs to monitor the <u>force</u> being exerted on the control stick in light of the previously mentioned aircraft metrics. A variety of pressure sensitive or infra-red chips could easily be incorporated unobtrusively into the control stick to monitor this phenomenon. A pressure sensitive chip would provide the advantage of quantifying grip strength vis-a-vis normal in cases (about 50%) in which an unconscious subject does not completely release the grip. Such a device could also be used to obtain information about the spectral content of stick inputs. A force measuring control stick has been developed in our laboratory and is shown in Figure 4.

d. Head Level Arterial Pulsations

From the early work of E. H. Wood it has been observed that loss of circulatory pulsations at ear level is followed, given a sustained acceleration stress, about five seconds later by loss of consciousness. Devices such as the ear opacity detectors used by Wood and subsequently by others would be difficult to incorporate into a LOCOMS and would violate the dictum that the sensor suite must be transparent to the pilot since the pilot would have to don the sensor. Several alternatives are currently under development.

One approach is based upon a dielectric patch antenna operating at 2.4 gigahertz and low power output (1 mw). This device is extremely sensitive to motion and is able to detect arterial wall motion when placed against the skin over an artery. Such a system has been developed for us by the David Sarnoff Laboratories at RCA (now MMTC Inc., Princeton, NJ), and an array of miniature sensors have been shown to work. At present a system using five such sensors built into an array inside a flight helmet has been constructed and tested (Mawhinney and Kresky, 1986; Mawhinney, 1988). The array is positioned over the occipital branch of the superficial temporal artery at the back of the head and can be integrated into a flight helmet. The system is very sensitive to helmet motion, however, and needs further development before it can become a potential LOCOMS "juror".

Current laser technology forms the basis for a second approach to the acquisition of pulse information. A commercial laser Doppler device (TSI Incorp, St Paul, MN) is under investigation for an unobtrusive method of obtaining transcutaneous capillary perfusion/pulse data and offers the potential for a system that could be incorporated in the oxygen mask without interference to other functions. This device is currently being evaluated using the Dynamic Environment Simulator.

A third possibility combines arterial oxygen saturation data with the acquisition of pulse data. A commercial product has been successfully integrated into the nasal portion of an oxygen mask (Tripp, 1988). The infra-red sensor reads SaO_2 and pulse data in the vicinity of the ethmoid artery on the nose and has been successfully tested under sustained acceleration. A side benefit is that this system may be capable of yielding SaO_2 data over extended multiple repetitive exposures which might be correlatable to fatigue and tolerance in a predictive manner in real time. This system is shown in Figure 5. Recent tests of this system at the Naval Air Development Center, Warminster, PA., have validated its potential as a non-intrusive LOCOMS.

A fourth possibility is the Transcranial Doppler (TCD) (Eden Medical Electronics, Kent, WA). This device actually monitors the flow of blood in the vertebral arteries. By directing high frequency, high intensity sound waves through the skull, the device is capable of recording arterial flow several inches into the skull. Thought, at first, to be the end-all sensor for a LOCOMS suite, the TCD has demonstrated that monitoring vertebral artery blood flow is not the ultimate physiological variable to monitor in determining loss-of-consciousness. Studies involving centrifuge subjects at AAMRL, Wright-Patterson AFB, USAF School of Aerospace Medicine, Brooks AFB, and more recently, at the Naval Air Development Center, Warminster, PA., have shown that even though vertebral artery blood flow can slow, and even stop temporarily, subjects can still maintain consciousness and perform (Werchan, 1990).

e. Spectral Shift in Frequency of EEG

Of all the sensors investigated to date for reliably determining GLOC, perhaps the most reliable indicator has been the EEG. In her studies at the USAF School of Aerospace Medicine, Lewis recorded the EEG on centrifuge subjects who voluntarily lost consciousness on the USAFSAM centrifuge (Lewis, 1988). She observed in the ten subjects who lost consciousness on the USAFSAM centrifuge, spectral changes in the EEG which are similar in nature to those observed during unconsciousness due to anesthesia, i.e., a striking power shift to lower (Delta) frequencies. Her conclusion was that the EEG can be used to detect unconsciousness in the high G environment, if the signal be can reliably and unobtrusively obtained. This requires the development of special electrodes.

Special, "dry" electrodes are currently being developed on a Small Business Innovative Research grant to Alan Gevins at SAM Technology, San Francico, CA. These non-preparatory electrodes require no gel or special preparations and could be integrated into a flight helmet. SAM Technology reports that this new system of "non-prep" electrodes has recorded EEG signals from subjects that are indistinguishable from those obtained using conventional EEG electrodes and amplifiers.

f. Presence/Quality of Anti-G Straining Maneuver (AGSM) and Anti-G Suit (AGS) Function

Both of these functions, assuming the necessary preliminary research, can easily be assayed by pressure transducers in the oxygen mask and the abdominal bladder of the AGS. Investigators have noted that the AGSM tends to "fade away" as a subject loses consciousness in a GLOC episode. It may be possible to quantify this "fading" in the form of an algorithm relating the pressure magnitude of exhalations, their pacing and intensity. AGS function can be made a simple go/no go signal from the abdominal bladder. McDonnell Aircraft, St. Louis, MO., has developed a transducer to monitor oxygen mask pressure.

g. Pilot Response to Voice Synthesized Interrogation

A system that does not provide the opportunity for pilot over-ride of the system is not likely to achieve user acceptance. For this reason it is assumed that, given a system decision in favor of GLOC, the LOCOMS should incorporate a voice synthesized query system for interrogating the pilot prior to intervention in aircraft control. This system will have to incorporate means for recognition of a response within some timeframe before intervention.

2. Integrated LOCOMS

An integrated LOCOMS has not been completed, to date. The candidate "jurors" in such a suite have been described above. The schematic of such a system is shown in Figure 6, where the best candidates are assembled in an artificial-intelligence driven package that is: 1) invisible to the pilot and, 2) interfaced with the 1553 mux buss of the aircraft. The AAMRL will continue pursuing the development of a LOCOMS which can be demonstrated in the near future.

3. Future Research

A research program for the investigation of the basic physiology of GLOC is currently underway at the USAF School of Aerospace Medicine (Werchan, 1989). This program will investigate the cellular basis for GLOC and hopefully lead to a better understanding of the phenomenon. Until a cellular basis can be identified, it may be useful to test a number of promising methods to shorten the period of pilot incapacitation following GLOC. Promising measures include the sustained or pulsatile inflation of the anti G suit. This measure would increase the recovering pilot's blood pressure by approximately 25mm Hg with the present generation AGS and would provide powerful kinesthetic stimulation to aid arousal. Such a system would require an electronically controllable AGS valve interfaced with the mux buss and the LOCOMS. Such a valve is being developed at the Armstrong Aerospace Medical Research Laboratory.

Loss of consciousness research at the AAMRL will focus on 1) recording as many physiological and psychological variables as possible from the volunteer subjects and 2) testing of the candidate juror subsystems in a LOCOMS. GLOC study results from both the USAF School of Aerospace Medicine and the Naval Air Development Center will be incorporated with the findings at AAMRL to develop a prototype LOCOMS by 1995. A future development will be the microprocessor-based algorithm that will analyze the aircraft and physiological metrics of the LOCOMS and decide whether or not the pilot is incapacitated.

Since the LOCOMS concept was introduced, the advances being made in neural network computing machinery have necessitated a complete re-thinking of the conventional serial von Neuman machine approach to the artificial intelligence aspects of the system. Today there are commercial off-the-shelf general purpose neurocomputing systems costing less than $20,000 which have been demonstrated to be capable of recognizing individual faces. A special purpose system of this type could be trained to recognize the physical/postural behavior of individuals losing consciousness under sustained acceleration and obviate most of the necessity for a sensor suite jury for the estimation of pilot physiological status. Such a system could actually be trained in a two seat fighter aircraft using unprotected subjects in the aircraft cockpit in order to obtain a wider and deeper knowledge base after having first been trained on video images obtained in human centrifuges. Such a system has been developed by the Information Systems Research Laboratory (ISRL) at the David Sarnoff Research Center, Princeton, NJ. ISRL developed the system for the Nielson Media Research Company. Nielson, the ratings company that helps networks determine what Americans watch on television, wants to place the systems on top of televisions in the homes of those 4000 dedicated TV viewers who are selected by Nielson in determining the most popular American TV programs. The smart sensing system recognizes faces in near real-time (Popular Science, 1990). Such a development would have tremendous potential for use in a LOCOMS. The problem of identifying a slumping head, with a helmet (visor up or down) is a much simpler problem than that of identifying an individual's face. Combining such a system, utilizing a miniaturized video camera, with a simple von Neuman expert system tracking aircraft altitude, attitude, and maneuver parameters would be a methodology offering great potential for an accurate and reliable LOCOMS. An initial list of attributes and values for a LOCOMS program is shown in Table I.

4. Enhancement of Recovery from G-LOC

An additional useful feature that might be added to the LOCOMS system would enhance recovery from a G induced loss-of-consciousness. During G-LOC there is a period of total incapacitation during which frank unconsciousness prevails. This has been termed the period of absolute incapacitation (Whinnery, 1986). Following nominal recovery, when the individual is "awake" and nominally responsive, there is an additional period during which the individual is in a confused state and not capable of purposeful action. This has been termed the period of relative incapacitation (Whinnery, 1986). It was suggested by Whinnery (1987) that attention ought to be given to reducing this period of partial incapacitation.

It is likely that the brain has been re-oxygenated to some threshold level when nominal recovery occurs. The arterial blood may well be resaturated, but it can be speculated that there is a biochemical/biophysical transfer function that defines the time required to transport oxygen across the cell walls in order to complete restoration of brain tissue oxygen levels. The use of 100% oxygen might shorten that time, and could be used on an experimental basis if the realities of cerebral neurophysiology indicate that there is any likelihood that it would be effective.

During this recovery period it is certain that artificially raising the pilot's blood pressure would cause no harm and could, conceivably, shorten the length of time for full recovery. There are at least three methodologies by which this might be done - hydrostatically, mechanically and pharmacologically. After a GLOC has been confirmed, a low negative Gz could be placed on the pilot by rolling the aircraft or placing it in an attitude that would result in negative Gz. Of course, such a maneuver could severly disorient a pilot recovering from a GLOC episode; this technique which relies on hydrostatics and the direction of the gravity vector, would necessarily require pilot advice for development. A recovery system to raise the blood pressure mechanically would require that the pilot's anti-G suit be inflated. A sequentially inflating anti-G suit (Van Patten, 1985) might be even more effective in this role because it would encourage the return of blood to the central circulation in a more natural manner than a conventional anti-G suit. This technique would require the use of an electrically or electronically controllable valve (Van Patten, 1985; Van Patten, 1986).

There are a number of pharmacological candidates. Carbon dioxide is known to enhance G tolerance because it increases peripheral vascular resistance and cardiac output, thus increasing mean arterial blood pressure. For a short period of time a mixture of 95% oxygen and 5% carbon dioxide could easily be administered via the oxygen mask. Acetazolamide, a compound similar in action to carbon dioxide and commonly used for the relief of altitude sickness, could be administered in the form of an aerosol to the oxygen mask and might be easier to implement than a carbon dioxide system unless such a system had been provided as a routine portion of an acceleration tolerance enchancement measure.

Subjecting the individual to a noxious smell could be of value in this period of GLOC recovery. Smelling salts have a long and time honored reputation and have the advantage of vigorously arousing the "reptile" brain since smell is the most primitive sense. A painful olfactory stimulus combined with voice synthesized exhortations might succeed in arousal in the cockpit as well as similar measures do in the intensive care unit.

What is certain is that the etiology of G-induced loss-of-consciousness and its sequelae are incompletely understood. Past research (Squires, et al., 1964; Berkout, et al., 1973; Cope, 1970; Reader, 1979; Marks, et al., 1969; Mitarai, et al., 1968; Jasper, et al., 1942; Adey, 1975; and Herraro, 1973) leads to the conclusion that some effect other than simple hypoxia is involved. It is hoped that work now in progress at the USAF School of Aerospace Medicine, the Naval Air Development Center and the Armstrong Aerospace Medical Research Laboratory will yield new insights into this process.

5. Conclusion

The crucial issue of operational utility of a LOCOMS system is pilot acceptance. Experience with the auto-save system demonstrated in the AFTI/F-16 has shown that a logic and aircraft-state system could do much to alleviate the loss of pilots and aircraft from the sequelae of G-induced loss-of-consciousness. A physiological state variable based system such as has been described here seems a natural for combination with an auto-save system and would result in enhanced reliability and reduced false alarm incidents, both of which would lead to greater acceptance and reliance on the system.

The development of high G training curricula for USAF pilots enrolled in lead-in fighter training at Holloman AFB, should greatly reduce the risk of GLOC. The development of an assisted positive pressure breathing system, called Combat Edge, will better protect Air Force pilots from long duration, high G exposures, and hopefully, help reduce GLOC statistics. Neither one of these developments, singly or together, will totally eradicate the GLOC problem.

Several individual sensors, which have been developed and tested at the AAMRL, offer promise to the eventual development of a Loss-of-Consciousness Monitoring System (LOCOMS) for high performance aircraft. The development of a microprocessor-based artificial intelligence system for a LOCOMS has yet to be developed but is entirely, technically feasible. All of this technology is commercially available at present and would allow the rapid development of such a system.

6. References

Mawhinney, D. D., and T. Kresky. Superficial temporal artery monitor. RCA Laboratories, David Sarnoff Research Center, Princeton, N.J. 08540. Harry G. Armstrong Aerospace Medical Research Laboratory, AAMRL-TR-86-008 March, 1986.

Gillingham, K.K., J.J. Freeman and R.C McNee. Transfer functions for eye-level blood pressure during +Gz stress. Aviat. Space Environ. Med. 48(11):1026-1034, 1977.

Whinnery, J. LOC recovery: its insidious nature. Proceedings of the FAA Aviation Medical Examiner Seminar: Session II Panel: G-Induced Loss-of-Consciousness. 57th Annual Scientific Meeting, Aerospace Medical Association, April 20-24, 1986.

Van Patten, R.E. Current research on advanced concept anti-G suits. 1985 Safety and Flight Equipment Association (SAFE), Riviera Hotel, Las Vegas, NV., Dec 2-4, 1985.

Van Patten, R.E. Development of an electro-pneumatic anti-G valve for high performance fighter aircraft. SAFE Journal, Winter Quarter 1985, Vol. 15, No. 4.

Van Patten, R.E. Advances in anti-G valve technology: what's in the future? Proceedings FAA Aviation Medical Examiner Seminar: Session II Panel; G-Induced Loss-of-Consciousness. 57th Annual Scientific Meeting, Aerospace Medical Association, April 20-24, 1985.

Saltzberg, B., and W.D. Burton. Analysis of electrophysiological signals from animals subjected to biodynamic stress. Texas Research Institute of Mental Sciences, Houston TX, 1979. Progress report No. 1, 1 May 77-Jul 79. Contract N00014-76-C-0911. DTIC AD-A073071.

Squires, R.D., R.E. Jensen, W.C. Sipple, and J.J. Gordon. Electroencephalographic changes in human subjects during blackout produced by positive acceleration. Naval Air Development Center, Aviation Medical Acceleration Laboratory, 1964. Report No. NADC-MA-6402, DTIC AD 438485.

Berkhout, J., R.D. O'Donnell, S.D. Leverett. Changes in electroencephalogram spectra during repeated exposure to +Gz acceleration. Final report, Contract AF 49 (636)-1387, Project AF-7184, Task 718405, AF Aerospace Medical Research Laboratory, Wright-Patterson AFB, OH. AAMRL-TR-72-123, June 1973. DTIC AD-764815.

Cope, F. W. Activation energies of acceleration and hypoxia stress. Naval Air Development Center, Warminster PA. July 1970. NADC Report Number NADC-MR-7015. DTIC AD-790569

Reader, D.C. Head acceleration and psychomotor performance. Aviation Space Environ. Med. 50(3): 267-70, March 1979.

Marks, E., and J. Miszczak. Influence of acceleration on electroencephalography in men. Acta Physiol. Poland, 20(5): 773-82, 1969.

Mitarai, G., T. Nagasaka, S. Mori, and S. Takagi. The effects of positive acceleration on the central nervous system. Presented paper, COSPAR, 11th Plenary Meeting, Tokyo, May 9-21, 1968.

Jasper, H., A. Cipriani, and E. Lotspeich. Physical studies on the effect of positive acceleration in cats and monkeys. Appendix R. National Research Council of Canada, Ottawa, Ontario, Canada. NRC-C-2225, 1942. DTIC AD-46175.

Adey, W.R. Neurophysiological estimates of human performance capabilities in aerospace systems. Air Force Office of Scientific Research, 1975. AFOSR-TR-75-0170. DTIC AD-A005690.

Herrero, A.P. The EEG of hypoxic and hyperoxic hypoxia in aviation and submarine medicine. Arch. Neurobiol. Madrid, Spain, 36(1): 31-46, Jan-Feb 73.

Van Patten, R.E. Current Research on an Artificial Intelligence-Based Loss of Consciousness Monitoring System for Fighter Aircraft. 24th Annual SAFE Symposium, 11-13 Dec 1986.

Hawkins, W. TV Views Viewers. Popular Science, 236, 2:74-75, Feb 1990.

O'Brien, P. Eyeblink Monitoring as a Means of Measuring Pilot Physiological State, 25th Annual SAFE Symposium, 16-19 Nov 1987.

Van Patten, R.E. Automatic Flight Path Recovery and Ground Avoidance: Physiological Assays for Loss of Consciousness Monitoring and the Role of Artificial Intelligence in the Air Combat Environment, Presented at the Annual Scientific Meeting of the Aerospace Medical Association, New Orleans Marriott, 8-12 May 1988.

Mawhinney, D. Flight Helmet Instrumented with Multiple Arterial Pulse Sensors, Proceedings of the National Aerospace and Electronics Conference (NAECON), Dayton, Oh 23-26 May 1988.

Werchan, P. Use of the Transcranial Doppler in G-induced Loss of Consciousness Research, to be presented at the 1990 ASMA meeting, New Orleans Marriott, Tues, 15 May 1990.

Whinnery, C. Enhancing Recovery from +Gz induced Loss of Consciousness, to be presented at the 1990 ASMA meeting, New Orleans Marriott, Tues., 15 May 1990.

Lewis, N. The EEG as an indicator of G-induced loss of consciousness (GLOC), 59th Annual Scientific Meeting of the Aerospace Medical Association, New Orleans Marriott, 8-12 May 1988.

Tripp, L. Development of a reliable non-intrusive, G-induced loss of consciousness monitoring device, 59th Annual Scientific Meeting of the Aerospace Medical Association, New Orleans Marriott, 8-12 May 1988.

Werchan, P. Rat Model for G-induced Loss of Consciousness, presented at the 59th Annual Scientific Meeting of the Aerospace Medical Association, 8-12 May 1988.

Albery, W. The Effect of Sustained Acceleration and Noise on Workload in Human Operators, Aviation Space Environ. Med., Vol 60 (10):943-948, 1989.

Table I
Initial List of Attributes and Values for Loss of Consciuusness Monitor (LOCOMS) Expert System

1. AC . ALT (AIRCRAFT ALTITUDE)
   Over . 10K (Current altitude is above 10,000 FT AGL)
   Under . 10K (Current altitude is below 10,000 FT AGL)
2. AC . ATT (AIRCRAFT ATTITUDE)
   Nose . Up
   Nose . Dn
3. AC . KNOTS (AIRCRAFT SPEED)
   Over . 40 (Current aircraft speed is above 400 knots)
   Under . 40
4. AC . GEES (CURRENT Gz STATUS)
   Any value between -5 and +12
5. AC . GDOT (CURRENT RATE OF CHANGE OF Gz)
   Any value between 0 and +6 G/SEC
6. PAST . GEES (HIGHEST Gz VALUE PULLED IN PAST 30 SECONDS)
   Any value between -5 and +12
7. PAST . GDOT (HIGHEST ONSET RATE PULLED IN PAST 30 SECONDS)
   Any value between 0 and +6 G/SEC
8. GSUIT . FN (IS G SUIT CURRENTLY PRESSURIZED)
   Yes/No
9. PAST . GSUIT (HAS G SUIT BEEN PRESSURIZED IN LAST 30 SECONDS)
   Yes/No
10. GRIP . STIK (DOES PILOT HAVE A GRIP ON THE STICK)
   Yes/No
11. GRIP . THROT (DOES THE PILOT HAVE A GRIP ON THE THROTTLE)
   Yes/No
12. HEAD . POSN (IS PILOT'S HEAD UPRIGHT)
   Yes/No
13. HEAD . MOV (IS PILOT'S HEAD MOVING)
   Yes/No
14. STRAIN . NOW (IS PILOT STRAINING RIGHT NOW)
   Yes/No
15. PAST . STRAIN (IF PAST . GEES > +4, HAS PILOT DONE STRAIN)
   Yes/No
16. BLINK . RATE (HOW MANY TIMES HAS PILOT BLINKED IN THE PAST 10 SEC)
   0, 1, >1
17. PULS . PAST (HAS THE SUPERFICIAL TEMPORAL ARTERY PULSE DISAPPEARED AT ANY TIME IN THE PAST 30 SEC)
   Yes/No
18. PULS . NOW (IS THERE A SUPERFICIAL TEMPORAL ARTERY PULSE NOW)
   Yes/No
19. EEG . STAT (HAS THE EEG SPECTRUM SHIFTED FROM ALPHA TO DELTA DURING PAST 10 SEC)
   Yes/No
20. SEIZE . STAT (HAS SEIZURE DETECTOR INDICATED SEIZURE ACTIVITY DURING THE PAST 10 SEC)
   Yes/No
21. STICK . STAT (HAS THERE BEEN STICK ACTIVITY IN THE SEIZURE FREQUENCY PASSBAND IN THE PAST 10 SEC)
   Yes/No
22. BLOOD . PRESS (HAS EYELEVEL BLOOD PRESSURE MODEL INDICATED ZERO BLOOD PRESSURE IN THE PAST 10 SEC)
   Yes/No
23. MARBLES . OK (HAS PILOT RESPONDED COHERENTLY TO SYNTHESIZED VOICE CHALLENGES)
   Yes/No

Block Diagram

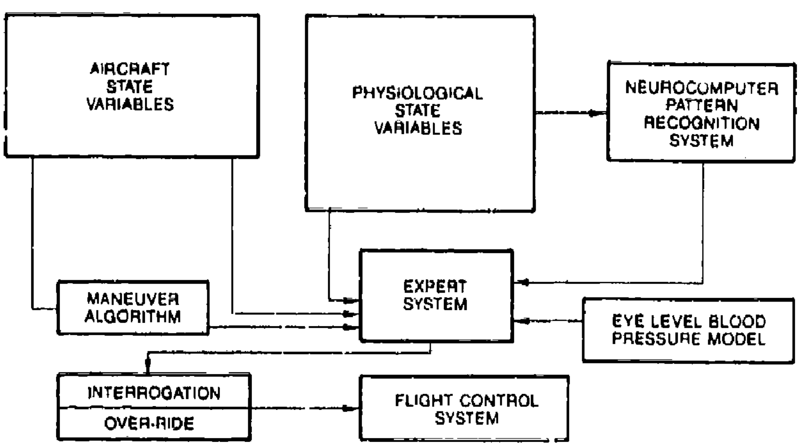


Figure 1. Interrelationship of Aircraft and Physiological Metrics in a LOCOMS

Figure 2. Eye Blink Detector

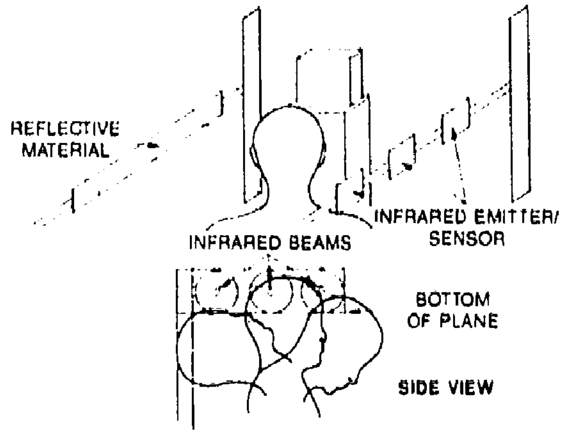
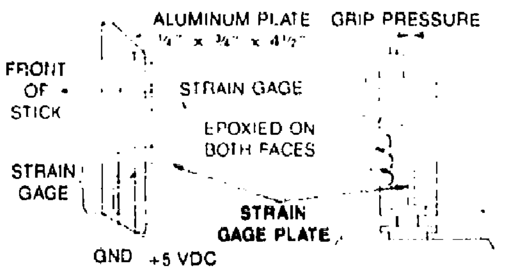


Figure. 3 Head Slump Detector



GRIP PRESSURE CAUSES A SLIGHT DEFORMATION OF ALUMINUM PLATE THUS DEVELOPING .. VOLTAGE ON BRIDGE MADE UP OF 2 STRAIN GAGES

Figure 4. Grip Strength Measuring Force Stick

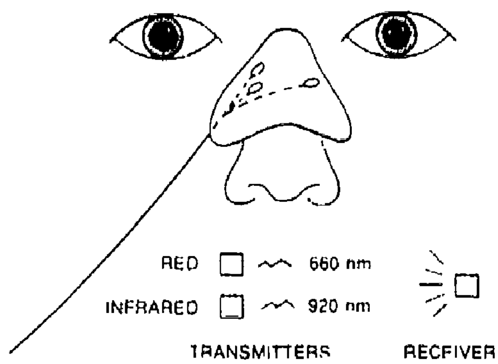


Figure 5. Pulse and SaO_2 Monitoring Oxygen Mask - Principle of Operation

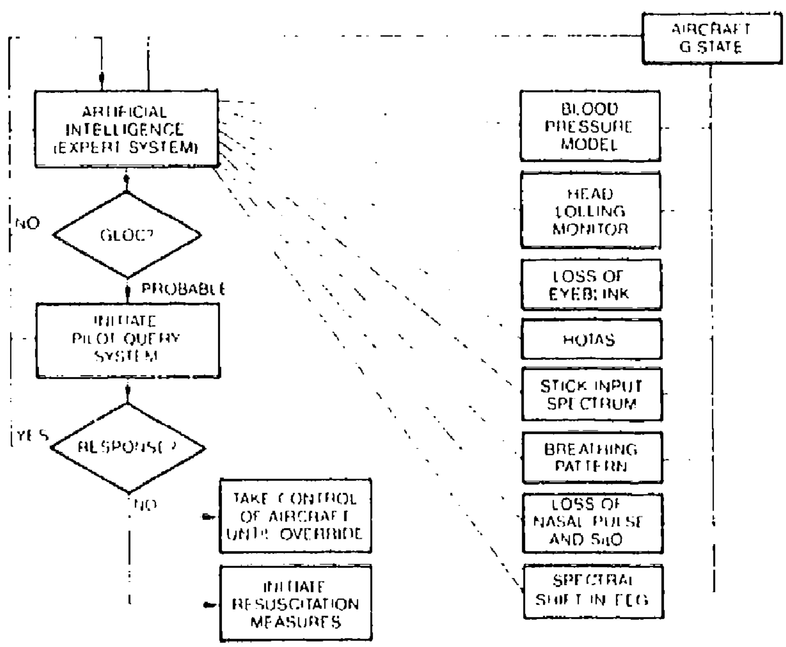


Figure 6. Integrated LOCOMS

Framework for an Efficient Two Filter GLOC Monitor

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SUMMARY

A multiple-filter GLOC design framework was derived. The framework recognizes the computational limitations of current and modified airborne avionics suites. The sequential gating approach minimizes load on supporting computer resources. As context and symptoms dictate, however, appropriate processing is applied. The framework is introduced as a provocative statement of design constraints inherent in 1970's jet architectures. The simplicity of design and implementation minimizes software engineering requirements, and holds hardware/interface development to but one requisite innovation--a helmet-integrated, ICS-capable earplug that would serve as a blood velocity, Doppler sensing and transdusing agent.

INTRODUCTION

Future tactical aircraft will be capable of phenomenal velocities, accelerations, as well as climb, and turn rates. According to many sources, included and summarized by the U.S. National Research Council (NRC; 1), vehicle dynamics improvements will be supported by numerous technological advances. A non-exhaustive summary of identified engineering gains is indicated in Table 1.

Table 1.

Technology	Target	Improvement	Enabler
Aerodynamics			
Drag reduction	Laminar flow control	20-25%	Active/passive concepts
	Turbulent flow control	25-30% subsonic	Pressure gradient muds, etc.
	Wave drag	10-15% supersonic	
	Induced drag	40% for fighters	Planform & structural changes
	Interference drag		Juncture & stores geometry
Vortex management			
	Active vortex control	Departure free configuration	
	T/O-landing separation	40-50%	Wake vortex alteration
Aero/propulsion integration			
	T/O-landing distances	Substantial	Thrust vectoring/reversing
	Lift enhancements	Double max lift	Low engine bleed propulsive lift
	Weight reduction	Improved perf/surv.	Adaptive inlets/nozzles
Propulsion			
	Engine internal temps	400°-600°F improvements	
	Compressor efficiency	80-90% for moderate-size compressors	
	Bearing rotational speed	To 3.5 milion DN	
	High speed propulsion	To mach 3.5 Æ12 regime	
Structures			
	Specific perf. parameters	Maximize aero. perf.	Adaptive wing shapes Chordwise, spanwise
	Temperature robustness	To temps expected on surfaces of cruise missiles	Low weight composites
	Propulsive systems	25-50% more efficient 50% less costly 50% T/W ratio 100% longer life	

The <u>human</u> consequence of vehicle dynamic improvements is very significant. Current tactical air missions are already recognized as being limited by human physiology and psychology. Without adequate protection (e.g., from G) or suitable enhancement (e.g, from informational overload), the improvements predicted for future <u>aircraft</u> in Table 1 will be only minimally exploitable by human <u>aircrews</u>.

Projected protections and enhancements will necessarily rely considerably on computational advancements. Data acquisition and processing capabilities, as indicated in Table 2, will accelerate much as those listed in Table 1.

To the extent that they are exotic (e.g., physiological inferencing techniques), successful pilot monitoring and recovery systems (PMRSs) will require robust sensors and very high speed data sampling and processing (DSP) capability. As indicated in Table 2, future aircraft will carry sophisticated computer machinery, with presumably adequate provision in software and hardware to incorporate exotic PMRS requirements.

Table 2.

Technology	Target	Improvement
Componentry	Cost effectiveness Size	2 orders of magnitude
Supercomputation	Processing Random access memory Execution rate Maintenance	To 100,000 elements 10 GWords 1,000 GFLOPS No unscheduled
MIL-STD systems	Processors RAM	1,000 MIPS 50 MWords
Fiber Optics	Capacity	25-50 Gbit/sec/fiber
Display systems	Resolution Local processing	8K x 8K pixels
		100-1,000 MIPS on 32 bit operands 50 MWords RAM 10-100 MWords rotating storage
Software	Architecture	Distribution Hetergenerty

The number of processors and processable bytes likely to board emerging aircraft is growing very rapidly. Future tactical aircraft, for example, will include 3-D digital integrated circuitry, as well as highly advanced componentry. Memory density will probably continue to increase--by an order of magnitude every five years. The avionics-computer industry expects to achieve between .5 and 1 gigabyte per sec, per optic fiber by year 2000. Likewise, processor organization will make tremendous gains: Massively parallel, distributed architectures will solve the enigmatic von Neumann ceiling, and we are likely to see airborne computers capable of 1,000 GFLOPS with upwards of 10 GWords of Random Access Memory (RAM) per processor. Similar advances will be evidenced in software technology. So-called artificial intelligence, including very sophisticated pattern recognition routines, expert advisory systems, and theorem provers will likely prove to be flight worthy within ten years.

For current inventory aircraft, the picture is soberingly different. Computer capability aboard current, and modified/current-generation tactical air platforms is quite modest by tomorrows standards. The current F/A-18, for example, is configured with two MIL-STD AYK-14 mission computers. Each AYK-14 supports 128K of core memory, 128K of EEPROM and 64K of RAM for a total memory capacity of 320K. Each AYK has five channel accesses to a MIL-STD 1553 data bus. This configuration, with both mission computers in operation, has a processing power of approximately 1.6 MIPS.

The F/A-18 C and D (lots 15 and above) architecture is based on a VHSIC (very high speed integrated circuitry) Processor Module (VPM) in each mission computer. The VHSIC processor will, in the near term, increase the processing power by half an order of magnitude, enabling the system to support approximately 8 million instructions per second. An additional channel will also be added to the F-18 architecture, resulting in six, total. These modifications are scheduled to be introduced by 1995.

Similarly, the current Navy F-14 is also configured with two AYK-14 mission computers, each with five MIL-STD 1553 data bus channels. The mission computers are not engineered like those of the F-18, however: Total memory capacity for the Navy Tomcat is only 868K. Memory is partitioned into 64K of core memory, 640K of EEPROM and 64K RAM. The net processing capability of the current F-14 mission computers is approximately 16 MIPS--similar to that of the F/A-18.

Within the context of the development of PMRS candidates, the importance of a clear understanding of on-board computational resources is essential. Whereas exotic means of pilot monitoring may be reliably supportable on future aircraft, today's computer memory and speed represent hard boundaries for the design of monitoring techniques in state of the art jets.

APPROACH

The present effort was aimed at producing a general framework for the design of a FMRS for current inventory tactical aircraft. The global engineering considerations for such a system are characterized in Figure 1.

An implication of Figure 1 is that, today, we are probably limited to human body interface design enhancements. These may be partitioned into two fundamental types: Those which require no physiological input (i.e., open loop) and those which do. The first are prophylactic measures; they are designed to improve net system G capability to some finite end point. One emerging example is a system which predicts G based on control stick dynamics to support the timely (pre-) inflation of pneumatic garments. Another is the baseline, or G-actuated elevation of the pelvis and lower limbs.

Physiologically-closed measures include (1) sophisticated means to assess conditions for GLOC occurrence, in order to condition a physiologically-based indication (e.g., impending GLOC) which then warn the pilot in order to allow him to relax stick pressure, reduce G, and restore physiological reserve; and (2) means to sense or infer pilot incapacity, and subsequently to recover control of the aircraft. The approach taken presently incorporated both of the closed loop measures.

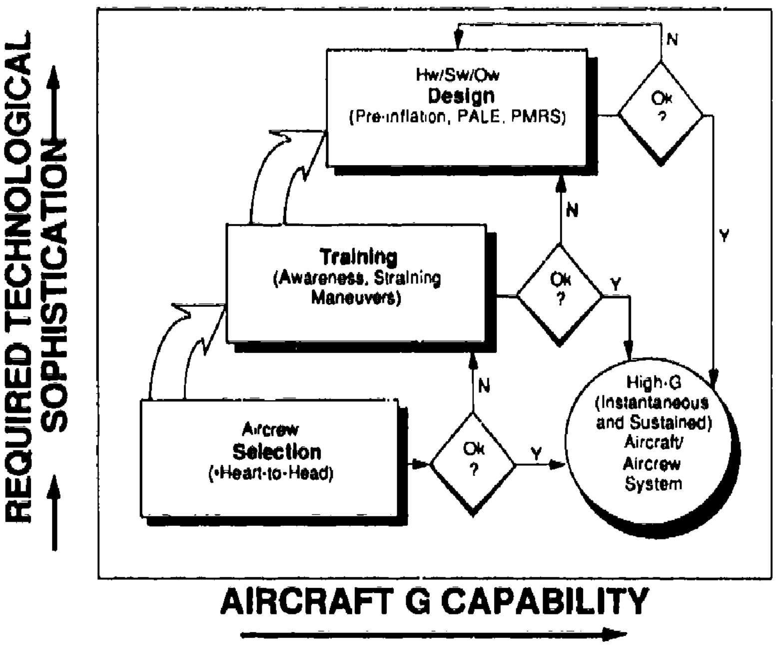

Figure 1. Requirements for G-protection. Progress in aircraft G ability has thrust us almost exclusively into the DESIGN-reliable phase

DESIGN FRAMEWORK

The design framework offered presently, honors the following five assumptions:

(1) demands on very limited computer resources must be prioritized throughout flight,

(2) context may be inferred on the basis of the physics of flight, and must serve as an input for prioritizing computer resources,

(3) a sequential gate system can be mechanized such that processing priorities may be managed with sufficient speed,

(4) a reliable helmet-integrated ear plug sensor can be engineered such that blood velocity Doppler soundings can be detected as depicted in Figure 2, and transduced, and, finally,

(5) such a system can be effectively integrated into, perhaps a not so accommodating human-machine system within which it is closed.

The fundamental logic is portrayed in Figure 3.

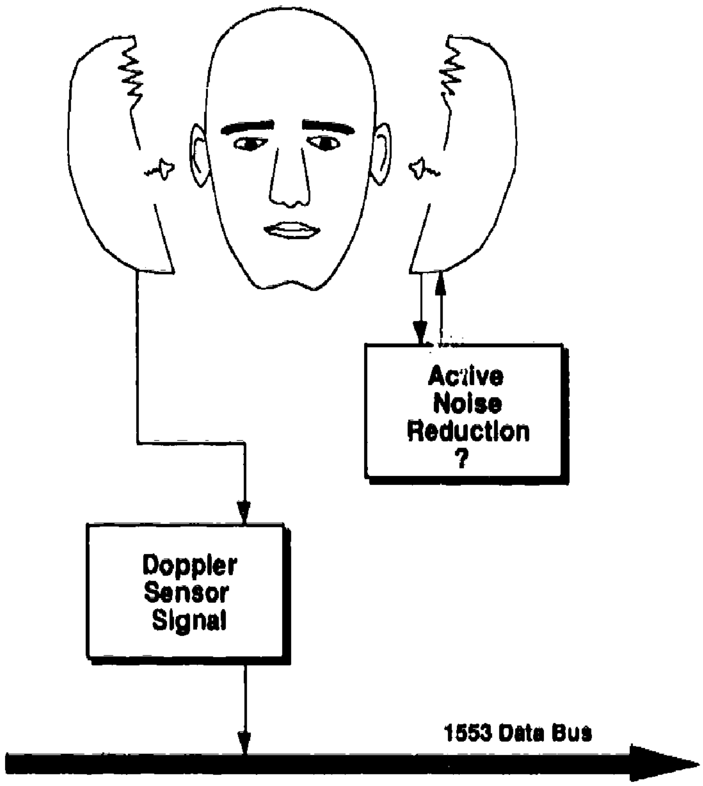

Figure 2. Earplugs engineered to sense blood flow acoustics. Doppler packaged and sent to mission computer via MIL-STD 1553 data bus. Active noise reduction could be integrated as well.

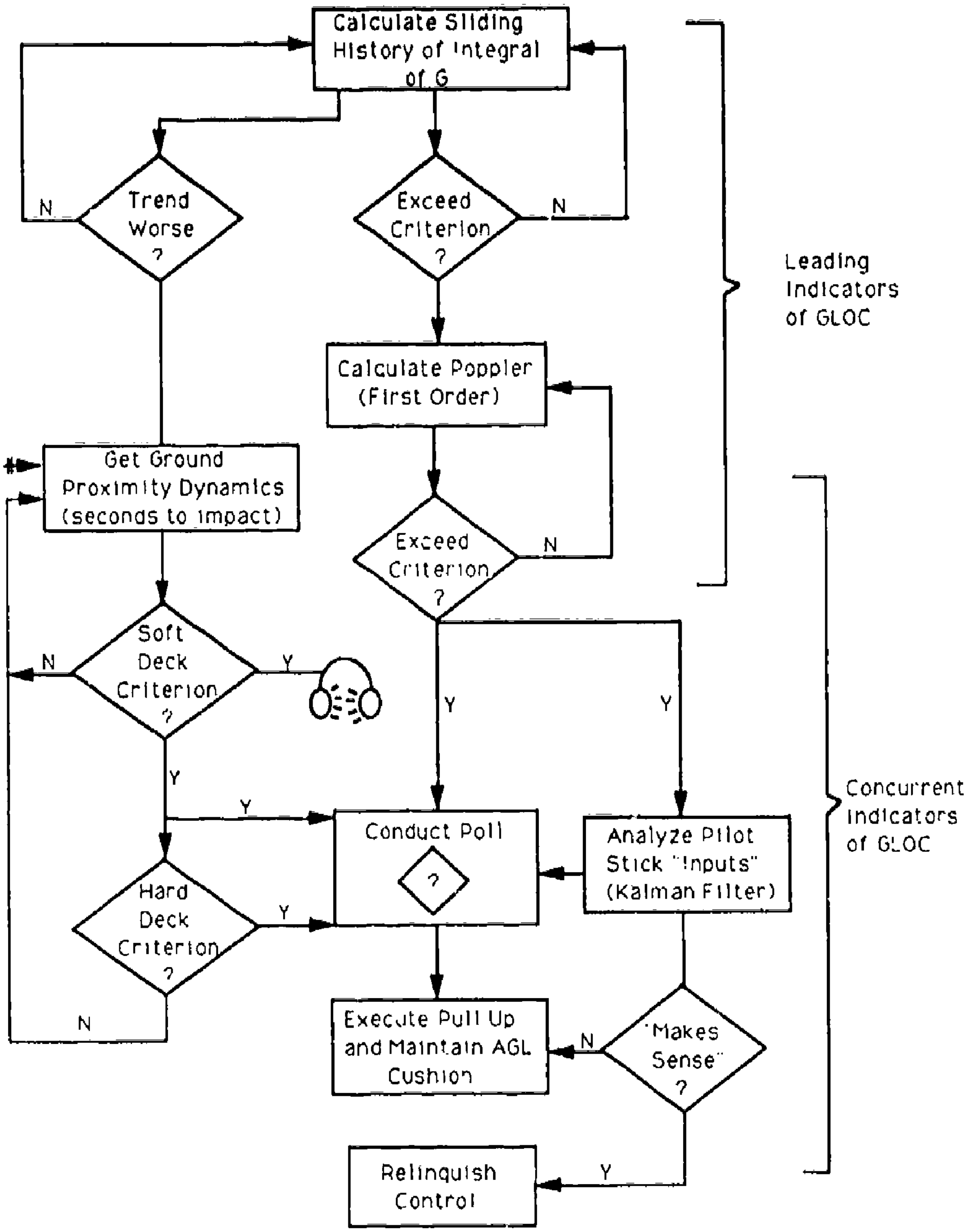

Figure 3. Basic Design Logic

Implementation

Implementation of the foregoing logic, as shown in the computer architecture diagram in Figure 4, requires software and hardware changes that imply modest engineering effort. The Operational Flight Program (OFP) resident in the AYK-14 would be modified to call a software routine designated FILTER1. This subroutine is an algorithm which provides a two-filter GLOC monitor.

The first stage of the algorithm takes the value of Gz from the 1553 databus and calculates a sliding numerical integration over time. This provides a measure of the total Gz sustained over a period of time termed, G-density (GDEN). When GDEN reaches a criterion value, the output from the Doppler sensor is monitored. It is not necessary to monitor the sensor output below criterion value, hence the extra load on the system is minimized. However, it must be ensured that the limen value is set low enough to allow for the wide variety of G levels at which GLOC occurs. The experimental data (Houghton, McBride, and Hannah, 1985, 2) show a tractable range across subjects, although research should focus on idiographics rather than group modeling. Most work, however, has concentrated on the construction of models based on nomothetical data (e.g., Burton, 3).

In the second stage of the algorithm, Doppler output is monitored and compared with a critical value. When the output falls below critical value, indicating imminent GLOC, a discrete variable is set true. Detection of the logical true state causes an aural warning tone to be emitted through the pilot's headset. When the pilot reduces the G load, the Doppler output falls below the critical value and the warning ceases. The measurement and monitoring of the Doppler output thus form the second filter.

Modifications Required to Existing Avionics

The two-filter GLOC monitor, as outlined above, can be incorporated into the OFP of the AYK-14. The primary modification to existing avionics required to implement the GLOC monitor is the addition of the algorithm FILTER1 to the OFP. The algorithm is short and does not require complex, time consuming operations.

Modifications to the 1553 databus traffic are such that the Doppler output of the sensor and the Gz are inputs to the AYK-14. The flag set within the OFP to indicate imminent GLOC must be output from the AYK-14 onto the databus. There are a number of spare discrete variables available within the OFP so the modificiation of software required is minimal. The flag should be monitored remote from the AYK-14, possibly within the communications (ICS) software, in order to generate the aural warning when the flag is set "on".

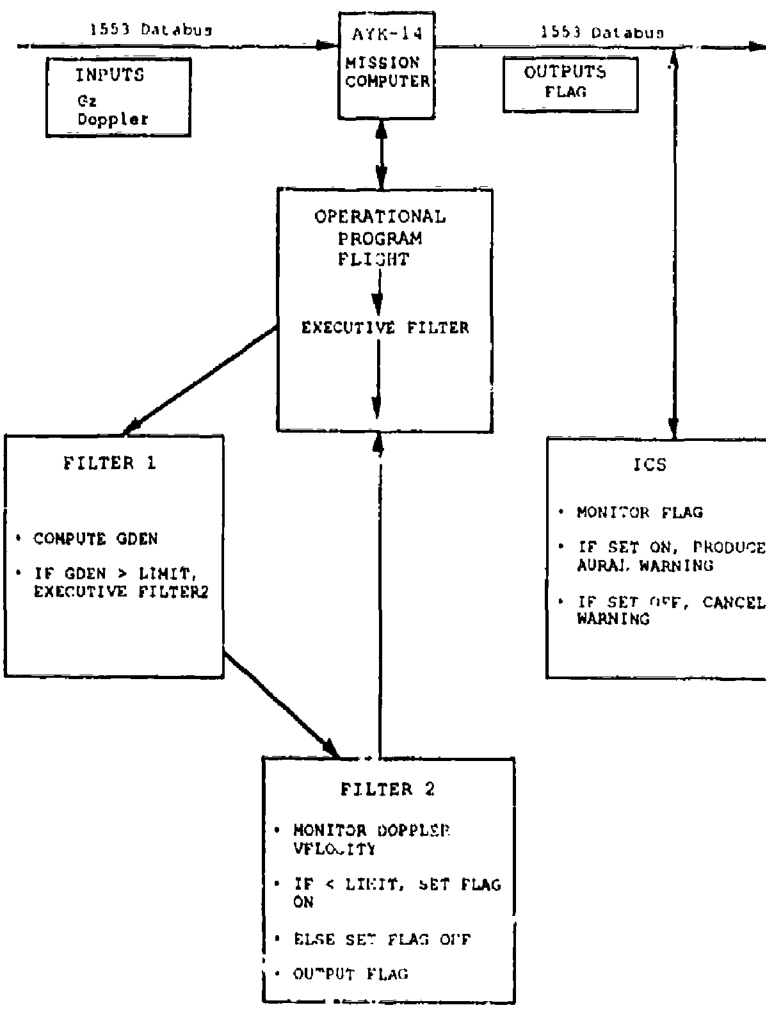

Figure 4. Avionics architecture for leading indicator, and first stage concurrent indicator GLOC gates

Concurrent Determinations of GLOC

If, despite the GLOC warning system, the pilot becomes unconscious, additional computing power is required to determine GLOC and to control the aircraft. There are a number of algorithmic methods to confirm (with Doppler data) GLOC, which could be operational based on selection by the pilot. For example, if the pilot has not made a "sensible" control input for a specifiable or context-dependent elapse of time, override is executed. The algorithms would likely use information from a ground proximity warning system. When GLOC occurs, computing resources would be reprioritized. With the pilot unconscious, of course, it is not necessary to maintain allegiance to ongoing computer regimen. In such case, the AYK-14 need not update the aircraft displays at their normal rate. Priority would dictate, rather, that adequate computer resources be directed to the GLOC problem.

CONCLUSIONS

A leading indicator filter was derived in order to (1) minimize data sampling and processing required of contemporary computer capability for predicting GLOC; the leading indicator filter in turn (2) actuates a concurrent indicator GLOC filter which is designed to ascertain pilot state accurately (with considerable but tactically acceptable computer burden) and initiate recovery. It appears that the processing load required to support the proposed architecture would be readily accommodated by U.S. Navy tactical aircraft avionics upgrades.

REFERENCES

(1) Aeronautics Technology Possibilities for 2000: Report of a Workshop. Aeronautics and Space Engineering Board, Commission on Engineering and Technical Systems, National Research Annual; 1984.

(2) Houghton, J.O., McBride, D.K. & Hannah, K., Performance and physiological effects of acceleration-induced (+Gz) loss of consciousness. Aviation Space and Environmental Medicine, 1985, 56, 956-965.

(3) Burton, R.R., A conceptual model for predicting pilot group G tolerance for tactical fighter aircraft. Aviation Space and Environmental Medicine, 1896, 57, 733-744.

A COMPARISON OF COMPUTERIZED MEASUREMENT OF HELICOPTER PILOT PERFORMANCE WITH ATROPINE SULFATE DURING ACTUAL AND SIMULATED FLIGHT

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Summary

The requirement for aviators to operate under stressful circumstances raises concerns over both safety and effectiveness. Although appropriate countermeasures for stress-induced performance deteriorations are available, the implementation of these countermeasures require that commanders know the time-course and extent of the problem. For this reason, the U.S. Army Aeromedical Research Laboratory has focused research on the practical assessment of helicopter pilot degradation using flight performance assessments which combine enhanced automation and objectivity with optimized data analysis procedures. Recently, the sensitivity, accuracy, and consistency of these assessment systems were demonstrated while studying the effects of atropine sulfate on aviator performance. Both simulator and helicopter systems detected atropine-related performance problems across a variety of aircraft control parameters. Also, analysis of combined simulator and helicopter data showed remarkable consistency of effects across the two flight platforms. This verification of performance measurement using computerized schemes in both simulator and aircraft has not only substantiated a feasible methodological approach, but has furthered the conceptual development of newer, portable assessment devices.

Introduction

Accurate measurement of pilot performance has been of interest to the aviation community for years. The implementation of new operational procedures, the fielding of appropriate pharmacological interventions (like antidote, pretreatment, and performance-enhancement drugs), and the improvement of training and tactical operations all would be facilitated if their effects on aviator performance could be accurately assessed. Particularly during the past 20 years, substantial progress has been made toward developing and refining various performance assessment strategies. Various approaches, both subjective and objective, have been developed and used, but many unanswered questions remain concerning the sensitivity and reliability of each approach.

Probably the most widely used assessment techniques involve subjective ratings made by either the pilot himself or a passive observer. Subjective ratings have been used to evaluate both aircraft handling qualities and actual pilot performance. For review see Lees and Ellingstad.[1] These rating systems have the advantages of face validity, low cost, and relative simplicity; however, they are susceptible to the sort of rater-induced variability which is particularly a problem in difficult or ambiguous tasks.[2]

Objective ratings of pilot performance bypass many of the undesirable factors associated with subjective assessments because the collected data are recorded directly from mechanical or electronic sensors and are analyzed by a computer. Objective measurement schemes have the advantages of being fast, efficient, and free of rater bias; however, they are often expensive and complicated, and straightforward data interpretations are sometimes elusive.

In spite of the current drawbacks with regard to the available assessment techniques, clearly there is a need for both subjective and objective measures of pilot performance which can be used in research and operational settings. Each strategy possesses relative strengths and weaknesses which must be considered on a situational basis before the optimal approach can be chosen and applied. It is then the task of each investigator to establish the sensitivity, reliability, and generalizability of any selected approach.

Researchers at the U.S. Army Aeromedical Research Laboratory (USAARL) capitalize on computerized assessments of pilot performance to examine the effects of a wide array of stressors in the belief performance changes can be accurately and objectively detected. Research performed in a 2-degree of motion helicopter operational training (HOT) simulator and an instrumented UH-1H helicopter relied upon computer-based measurements to detect performance degradations induced by atropine.[3-4]

Here, we will demonstrate the feasibility of assessing pilot performance with computerized systems as well as the degree to which potential in-flight problems may be accurately established using a ground-based simulator. Since this report stems from two studies involving the same stressor (atropine) and similar designs, we will also show both the sensitivity and consistency of two analogous computer-based performance assessment systems.

Method

Subjects. Twenty-four U.S. Army helicopter pilots were used to collect the data reported here. Twelve of these subjects participated in a simulator assessment of atropine, and 12 were involved during in-flight atropine testing. These subjects were between the ages of 21 and 35, and possessed uncorrected 20/20 vision and normal hearing.

Apparatus. The performance measurement system used in the simulator[5] collected data on heading, altitude, airspeed, pitch, roll, trim, climb rate, turn rate, instrument landing system (ILS) localizer, ILS glide slope, and several other parameters. Data were collected from the 2-degree of motion simulator using an Electronic Associates Incorporated (EAI) 681 analog computer interfaced with a Digital Equipment Corporation (DEC) LPA-11K microprocessor and a DEC VAX 11/780 computer. Channels were sampled at a rate of up to 20 times per second. Specialized software provided real-time processing capability, control of maneuver sequencing, and data storage, but the performance data were analyzed off-line.

The helicopter in-flight system[6] collected data on aircraft measures similar to those collected from the simulator. However, rather than transmitting these data directly to the VAX computer, the data were stored on magnetic tape during flights and later transferred and prepared for analyses. Sixty-four channels were available, but only a subset was used for this study. Again, a maximum rate of 20 samples per second on any given channel was employed. This was accomplished with a helicopter-mounted system consisting of a computer unit, signal conditioner, and tape-terminal unit. The system was powered either directly from the helicopter's 28 volt supply, through DC/AC converters, or through a 115-volt power inverter (depending upon the component).

Flight performance data collected from both the simulator and the helicopter were analyzed with the same type of scoring routines. These routines calculated root mean square (RMS) errors for each measured parameter (airspeed, altitude, etc.) during each maneuver (delimited by a marked starting and ending point). The RMS errors depicted the standard deviation of a subject's performance around some ideal standard. For instance, if a subject consistently flew at 991 feet when he was supposed to fly at 1000 feet, this resulted in an RMS error of 9 feet.

Procedure. In both the simulator and in-flight phases of this research, each subject was exposed to three dose conditions (placebo, 2 mg, and 4 mg atropine sulfate) on different days. Subjects did not know which drug dose they were receiving. The drug or placebo was given via injection into the thigh muscle immediately preceding the morning flight. Each subject flew two flights on each dosage administration day, with the first flight occurring immediately after injection and the second flight occurring about 5-6 hours later. Each flight lasted approximately 2 hours, during which subjects flew a variety of maneuvers. Each day on which an active drug was given was followed by a control day to provide 24 hours for the last dose to clear the body before the next dose was given.

The flight profile in the simulator study consisted of several components of a standard instrument flight which included an instrument takeoff, navigation and flight to a destination airport (which contained a straight-and-level segment), holding at the instrument landing system (ILS) outer marker, and an ILS approach. The instrument takeoff and holding at the ILS outer marker were not scored by computer, but they were graded by a safety pilot. At one point during the profile, subjects were required to complete a variety of precision maneuvers in which specific headings, altitudes, and airspeeds were maintained for designated periods of time. Additionally, subjects were required to perform a 180-degree standard-rate climbing turn and a 180-degree standard-rate descending turn.

The in-flight profile consisted of a series of upper-air maneuvers which included two standard-rate flat turns, five straight-and-level segments, two steep turns, a 360-degree descending right turn and a 360-degree climbing left turn, a straight climb, and a straight descent. This section of the profile was followed by confined area operations, low-level and nap-of-the-earth (NOE) navigation, and a vertical helicopter instrument flight rule (IFR) recovery procedure--these last four maneuvers were scored only by a safety pilot and not by computer. The profile terminated with a final instrument straight-and-level and an ILS approach into an Army airfield.

Results

Data were analyzed with BMDP4V statistical software[7], repeated measures analysis of variance. The factors were dose (placebo, 2 mg, 4 mg), flight (a.m./p.m.), and sometimes maneuver (where similar maneuvers were analyzed together). Missing data from one flight of one subject during the in-flight study, resulting from a flight termination because of excessive heart rate, were estimated with BMDPAM (Dixon et al., 1983) using the cell means of existing data. Missing data because of ILS glide slope malfunction on three flights (also during the in-flight study) were estimated with the same procedure.

Although a large number of significant effects were obtained from both studies, this paper presents only the significant dose main effects and dose by maneuver interactions when considering the two studies separately. When both data sets are combined, all significant effects are reported.

To address issues regarding the sensitivity of computerized assessments of pilot performance, the simulator and in-flight data were analyzed separately. For this level of analysis, the RMS errors from the simulator study were corrected for practice effects and subjected to log-natural transformations prior to analysis. The RMS errors from the in-flight study were only log-natural transformed since practice effects had been minimized at the outset of this study by implementing training sessions on the flight profile prior to the first dose administration.

To address issues regarding the comparability (and consistency) of simulator and in-flight assessments, the simulator and in-flight data were analyzed in combination. For this level of analysis, it was necessary to standardize the data from each set before they were combined and analyzed. Thus, each data set was independently subjected to a z-score transformation which resulted in comparable measurement units between the two.

Simulator Performance

Descending and climbing turn. There were no main effects of atropine on any pilot performance measures for the descending turn; however, the climbing turn showed an effect on vertical speed accuracy ($F(2,22)=4.49$, $p=0.0232$). Here, performance was poorer under 4 mg atropine than under either 2 mg or placebo ($p<.05$).

Straight and level. The straight and level segment was affected by atropine on a number of measures. There were dose effects on control of heading ($F(1.28,14.13)=7.47$, $p=0.0177$), altitude ($F(2,22)=8.17$, $p=0.0022$), airspeed ($F(2,22)=13.30$, $p=0.0002$), and vertical speed ($F(2,22)=10.60$, $p=0.0006$). Heading and vertical speed errors were greater under 4 mg and 2 mg than under placebo, while the altitude and airspeed errors were significantly greater only under the 4 mg dose ($p<.05$).

Sequential upper-air maneuvers. The series of maneuvers which required subjects to execute changes in heading, altitude, and/or airspeed for a specific period of time also indicated an atropine-induced performance decrement on heading ($F(2,22)=7.42$, $p=0.0034$). Heading control errors were greater under 4 mg than under either the 2 mg or placebo dose ($p<.05$).

Instrument Landing System (ILS) approach. Analysis of performance measures on the instrument landing system approach revealed only a marginal atropine-related effect on runway localizer (centerline) error ($p=.0541$). Posthoc analysis showed this effect resulted from a higher RMS error under 4 mg atropine as compared to 2 mg ($p<.05$).

In-flight Performance

Straight and level. During the in-flight investigation, subjects performed several straight and level (SL) maneuvers. The first five of these (SLs 1-5) were conducted using visual references, and the last one (SL 6) was conducted using instruments only while "under the hood." There were atropine effects across all of these maneuvers on heading (SL 1-5, $F(2,22)=4.10$, $p=0.0307$; and SL 6, $F(2,22)=4.59$, $p=0.0215$), and on the last one (SL 6), there was also an effect on airspeed control ($F(2,22)=6.16$, $p=0.0075$). Heading control during the first five straight and levels was substantially reduced ($p<.05$) under 4 mg as compared to placebo and marginally reduced ($p=0.0595$) under 4 mg as compared to 2 mg. On the sixth straight and level, heading control was worse under 4 mg than under either of the other doses ($p<.05$). Airspeed control was apparently improved under the 2 mg dose in comparison to placebo and 4 mg ($p<.05$).

Standard-rate and steep turns. Examination of performance during the two standard-rate level turns did not reveal any dose main effects or dose by maneuver interactions. Also, performance on the two steep turns was unaffected.

Straight climb and descent. Analysis of the straight climb and the straight descent indicated atropine effects on both heading control ($F(2,22)=6.64$, $p=0.0056$) and roll control ($F(2,22)=3.54$, $p=0.0464$). Subsequent contrasts showed both of these measures suffered from increased error under the 4 mg condition as compared to placebo ($p<.05$).

Climbing and descending turn. The climbing and descending turns, analyzed together, also revealed atropine effects. Specifically, there was a dose main effect on the airspeed control measure ($F(2,22)=3.61$, $p=0.0441$) which at first suggested airspeed errors were increased by atropine during both of these maneuvers. However, there was also an interaction between dose and maneuver ($F(2,22)=5.98$, $p=0.0085$) which subsequent analyses of simple effects indicated to be because of a dose effect during only the climbing turn ($F(2,22)=9.18$, $p=0.0013$). Further examination of atropine effects during just the climbing turn showed that airspeed errors were greater under 4 mg than under either 2 mg or placebo ($p<.05$).

Instrument Landing System approach. Performance with regard to airspeed control during the instrument landing system approach also was affected by atropine ($F(2,22)=4.09$, $p=0.0308$). In this case, the 4 mg dose contributed to greater control error than did the placebo dose ($p<.05$) as was found in several other maneuvers.

Combined Simulator and In-flight Performance

To establish the comparability of performance evaluations made in the simulator and in the helicopter (and the consistency across time), maneuvers which were common to both studies were extracted for additional analyses. Also, only the identical measures (i.e., airspeed, heading, altitude, etc.) from both data sets were used since any other approach would have yielded an incomplete design structure. The maneuvers and measures analyzed are presented in Table 1 (along with the average elapsed time from dose for each).

After dissimilar maneuvers were discarded, both sets of transformed RMS errors were standardized by applying z-score transformations to all measures from each maneuver (treating each flight as a separate case) in the two data files separately. Following the transformations, the two data files were merged for repeated measures analysis of variance.

The maneuvers selected for analysis consisted of 1) instrument straight and level, 2) climbing turn, 3) descending turn, and 4) ILS. Each maneuver was analyzed in a separate analysis of variance with a single grouping factor (simulator vs. aircraft) and two repeated measures factors (dose and flight). The primary reason for conducting these analyses was to determine whether simulator performance was affected the same way by atropine as was in-flight (or aircraft) performance, because this would offer insight into the comparability of pilot performance in the two devices (simulator/aircraft) and the comparability of computerized measurement systems used in both. Therefore, the existence of device (simulator/helicopter) by dose interactions deserves the most attention of any of the observed effects.

Straight and level. The analysis where the instrument straight and level in the simulator was compared to the instrument straight and level in the aircraft revealed dose main effects on control of heading ($F(2,44)=10.94$, $p=0.0001$), altitude ($F(2,44)=8.20$, $p=0.0009$), airspeed ($F(2,44)=16.03$, $p=0.0000$), and vertical speed ($F(2,44)=11.17$, $p=0.0001$). These were due to more control errors under 4 mg than under both 2 mg and placebo ($p<.05$). However, there was not a difference between the 2 mg and placebo conditions (Figure 1).

There were also a couple of device (simulator/helicopter) by dose interactions, one of which was found on airspeed control ($F(2,44)=4.75$, $p=0.0136$), and the other of which was found on vertical speed control ($F(2,44)=5.52$, $p=0.0073$). Analyses of simple effects revealed the airspeed control effect was somewhat complex since there was a dose effect in both the simulator ($F(2,44)=15.94$, $p=0.0000$) and the helicopter ($F(2,44)=4.84$, $p=0.0126$). However, the dose effect in the simulator was the larger of the two. In the simulator, the effect was attributed to greater airspeed control errors under 4 mg than under both 2 mg and placebo ($p<.05$). In the aircraft, the dose effect was due to greater errors under 4 mg than under 2 mg ($p<.05$). This interaction is depicted in Figure 2.

Analyses of simple effects on the vertical speed interaction showed there was also a dose effect in the simulator ($F(2,44)=15.38$, $p=0.0000$), but a similar effect was absent in the aircraft (see Figure 3). Contrasts revealed the dose effect in the simulator was due to higher errors under 4 mg and under 2 mg than was the case under placebo.

In addition to these dose-related effects, several differences were attributable to whether the flight took place in the morning or afternoon on altitude ($F(1,22)=10.01$, $p=0.0045$), airspeed ($F(1,22)=27.13$, $p=0.0000$), and vertical speed control ($F(1,22)=42.53$, $p=0.0000$). Also, there was a device by flight interaction on these same measures with the addition of heading (altitude: $F(1,22)=14.93$, $p=0.0008$; airspeed: $F(1,22)=30.86$, $p=0.0000$; vertical speed: $F(1,22)-30.57$, $p=0.0000$, and heading: $F(1,22)=8.54$, $p=0.0079$). Overall, performance on altitude, airspeed, and vertical speed seemed best in the afternoon.

When the devices (simulator or aircraft) were examined in isolation, it could be seen the amount of change from one flight to the other was greater in the aircraft than in the simulator on every measure except heading as can be seen in Figures 4, 5, 6, and 7. Lastly, for the straight and level data, there was a significant 3-way interaction (device by dose by flight) on altitude control ($F(2,44)=3.21$, $p=0.0502$). This effect was apparently due to an interaction in the aircraft data between dose and flight. However, the effect was only marginal ($p=0.0619$), so it was not pursued further.

Climbing turn. Analysis of airspeed and vertical speed control during the climbing turns in the simulator and in the aircraft showed relatively few effects. On the airspeed control measure, there was only one significant effect, and this was an interaction between device and dose ($F(2,44)=3.70$, $p=0.0326$). Analyses of simple effects indicated the effect was because of differences among the dose conditions in the aircraft ($F(2,44)=6.04$, $p=0.0054$) which were absent in the simulator (see Figure 8). Subsequent contrasts pinpointed the nature of this effect as reductions in helicopter control accuracy under 4 mg as compared to both 2 mg ($p=.0526$) and placebo ($p=.0538$). That this same effect was not present in the simulator may have been partially because only a half turn was required in the simulator rather than the full turn used in the helicopter.

Examination of the vertical speed measure detected no similar device (simulator versus helicopter) by dose interaction; however, there was a dose main effect ($F(2,44)=8.78$, $p=0.0006$) and a device by flight interaction ($F(1,22)=6.66$, $p=0.0171$). The overall dose effect was due to significant decreases in control accuracy under 4 mg as compared to both the 2 mg and placebo doses ($p<.05$). This may be seen in Figure 9.

The device by flight interaction (Figure 10) was due to a substantial improvement in vertical speed control in the aircraft during the afternoon as compared to the morning ($p<.05$). This same effect was not present in the simulator data.

Descending turn. Analysis of airspeed and vertical speed during the descending turn indicated there were no dose-related effects on this maneuver in the simulator or the helicopter. However, there was an overall flight (morning versus afternoon) main effect on airspeed control ($F(1,22)=5.46$, $p=0.0290$), and there was a device by flight interaction on both airspeed ($F(1,22)=7.75$, $p=0.0108$) and vertical speed measures ($F(1,22)=9.27$, $p=0.0059$). The main effect indicated better overall control in the afternoon than in the morning. However, the interactions were due to better control in the afternoon than in the morning during only the in-flight study ($p<.05$), as can be seen in Figures 11 and 12. There were no morning versus afternoon effects in the simulator.

Instrument landing system. To examine performance on the ILS, measures of airspeed, localizer tracking, and glide slope tracking were analyzed. Dose main effects were found on both airspeed ($F(2,44)=4.21$, $p=0.0212$) and localizer ($F(2,44)=3.68$, $p=0.0334$). These were attributed to poorer control under 4 mg than under either 2 mg or placebo ($p<.05$ except for the 4 mg to placebo comparison on localizer where $p=.0603$). These effects are depicted in Figure 13.

In addition to the dose-related effects, there were also flight main effects on airspeed ($F(1,22)=15.81$, $p=0.0006$) and glide slope errors ($F(1,22)=5.78$, $p=0.0251$), and a device by flight interaction on glide slope errors ($F(1,22)=7.46$, $p=0.0122$). The flight main effects indicated better overall performance in the afternoon than in the morning. The interaction on glide slope control was due to the same type of flight effect which was large enough only under the in-flight conditions to attain significance ($p<.05$). There was no difference between the two flights in the simulator data. This interaction is depicted in Figure 14.

Discussion

The overall picture presented by the analyses of flight performance data from the simulator and in-flight atropine studies suggests 1) high sensitivity of computerized assessments, 2) basic comparability between assessments made in the two flight platforms, and 3) consistency of these assessments across time. Of the 11 measures (from 4 maneuvers) examined, there were 7 dose main effects and only 3 device (simulator vs. helicopter) by dose interactions. These findings suggest performance in both simulator and aircraft, and the measurement schemes used to assess this performance were sensitive to the effects of atropine. Also, the level of sensitivity was largely comparable between the simulator and helicopter environments. A visual examination of standardized mean performance across the variety of measures used here depicts strikingly similar effects of the two atropine doses on flight performance regardless of whether it was observed in the simulator or in the helicopter.

Atropine main effects were significant on measures of heading, altitude, airspeed, and vertical speed control during the straight and level maneuver. There were also significant atropine effects on vertical speed control during the climbing turn, and on airspeed control and localizer tracking during the instrument landing. In every case, the 4 mg dose produced the poorest performance. In five of the seven cases, there appeared to be a linear decline in performance as a function of dose, but the difference between 2 mg and placebo was not significant. In the remaining two cases, it appeared that performance was best under 2 mg, but the difference between 2 mg and placebo was not significant here either.

The interactions which were inspected to detect differing dose effects as a function of whether pilots were flying the simulator or the aircraft were very few in number. Only three of these device by dose interactions were significant. Measures of airspeed and vertical speed control during the straight and level maneuver revealed a greater atropine impact in the simulator than in the aircraft. Here, there was an atropine effect in the simulator with regard to both of these measures, whereas there was only a difference in the aircraft on airspeed control.

Visual inspection of mean performance revealed a tendency for helicopter control to have often remained about the same under the placebo and 2 mg conditions (occasionally there appeared to be an improvement under 2 mg), while simulator control generally seemed to be reduced by the 2 mg dose relative to placebo. This made it appear that simulator control often was better than aircraft control under placebo, whereas simulator control often appeared worse than aircraft control under both 2 mg and 4 mg. This picture of atropine effects was observed on almost every measure during the straight and level maneuver; however, the differences were not significant.

The device (simulator vs. helicopter) by dose interaction found on airspeed control during the climbing turn was different from what was seen in the straight and level. Atropine apparently exerted no influence over airspeed control in the simulator, whereas significant decrements due to 4 mg was seen in the aircraft. It is possible this difference was due to the use of a 180-degree turn in the simulator as opposed to the 360-degree turn in the helicopter.

Taken together, these findings support the suggestion that atropine effects were comparably assessed in the simulator and the aircraft. Two of the three significant interactions between device and dose indicated similar atropine effects in both.

However, a visual inspection of some of the data suggests there may have been less of a difference between placebo and 2 mg in the aircraft than in the simulator. Such a difference (often not significant in this study) may have been because it was easier to precisely fly the simulator than the aircraft under placebo since factors like air turbulence were not present in the simulator study. Such differences probably were not attributable to unreliable performance measurement.

One other set of findings which deserves notice relates to the comparability of simulator and aircraft with regard to time-of-day effects. Here, it was observed there were device by flight interactions on 8 of the 11 measures. Control accuracy on heading, altitude, airspeed, and vertical speed during straight and level; vertical speed during the climbing turn; airspeed and vertical speed during the descending turn; and glide slope tracking during the instrument landing were all affected differently by time of day in the aircraft as opposed to the simulator. In every case except one, there was significantly better performance in the afternoon than in the morning in the aircraft, but not in the simulator. The single opposite effect involved heading control during straight and level where there was a flight difference (morning better than afternoon) in only the simulator. Reasons for this single divergent effect still remain unclear.

Since these device (simulator/helicopter) by flight (a.m./p.m.) interactions were independent of any dose effects, some other factor is responsible for the observed differences. One plausible explanation centers around subjects' apprehensions concerning the possible dose effects. Each subject received an injection prior to each morning flight, and he was not told which dose would be administered. Thus, he simply began the flight and waited for whatever drug effects were anticipated. Once the drug effects became evident, he no doubt wondered how extensive these effects would be before they leveled off. It is reasonable to speculate there was a great deal of anxiety during the morning flight. However, by the time of the afternoon flight, the subjects not only were aware of whether they had received an active or placebo dose, they were also aware of how extensive the drug effects would be and how much of a performance problem the drug would create. No doubt, by the time of the afternoon flight, most subjects were convinced they could perform the required tasks even under the influence of atropine. Thus, they were able to concentrate more on controlling the aircraft without being distracted by worrying about the potential impending effects of atropine.

The fact that this significant improvement from morning to afternoon was usually seen in the aircraft and not the simulator probably stems from the subjects' having more reason to worry about drug effects in the air. Crashing a simulator is really inconsequential in comparison to crashing an aircraft. Thus, this difference in flights between the two devices (simulator vs. aircraft) probably reflects the subjects' realistic awareness of the consequences of a serious performance decrement in the different situations.

This awareness also may explain at least part of a couple of device by dose interactions discussed earlier. During the straight and level maneuver in the helicopter, there was no reduction in performance between the placebo and 2 mg doses whereas the 4 mg dose, at least in one case, produced a significant decrement. Visual inspection of the means suggested the 2 mg dose was sometimes associated with performance which appeared better than performance under placebo (in the helicopter). However, during this same maneuver in the simulator, a different relationship was seen. Here, there was a fairly linear decrease in performance as a function of dose particularly with regard to vertical speed control. Perhaps the subjects flying the aircraft worked hard to combat the performance degrading effects of atropine, and this work paid off under the smaller dose. Conversely, since the subjects flying the simulator were not in a potentially life-threatening situation, they did not feel the need to exert this extra energy to guard against slight performance decrements, so their performance under the smaller dose appeared degraded. Of course, once the larger dose of atropine was administered, it did not appear to matter which device the subjects were flying. The 4 mg dose was usually powerful enough to produce a reliable worsening of performance in both situations.

In summary, the important findings are that both simulator and helicopter computerized measurement systems are consistently sensitive to the effects of atropine, and any differences between simulator and helicopter results can be explained on the basis of actual differences in pilots' performance rather than instability of the performance measurement schemes. Whether in the simulator or in the helicopter, the computerized monitoring systems generally provided reliable assessments of atropine effects. Also, it should be noted that the simulator and in-flight studies were conducted about 2 years apart, and the consistent results substantiate the dependability of accurate computerized assessments over time.

Conclusions

Analysis and comparison of the results from similar portions of a simulator atropine study and an in-flight atropine study were conducted to determine the sensitivity of computerized assessments of pilot performance and the comparability of assessments made in a simulator and in an actual helicopter. Generally, it was found that both flight platforms and their associated performance measurement systems were sensitive to atropine effects and this sensitivity was consistent across time. There were a few instances where the impact of atropine was significantly different depending on whether it was observed in the simulator or in the aircraft; however, in most instances performance as a function of atropine in the two devices (simulator/aircraft) did not differ. In addition, a couple of the observed simulator/helicopter differences probably resulted from a combination of environment and motivation rather than from a lack of measurement reliability. Specifically, in the simulator there was no air turbulence and there was no threat of actual loss of life. The first factor may explain the tendency toward better simulator than aircraft performance under placebo, while the second factor may explain the absence of a performance decrement between the placebo and 2 mg conditions in the aircraft. Also, the simulator and its associated measurement system probably did not offer the fidelity found with the helicopter. However, it should be reiterated, there were most frequently no differences between the atropine effects as a function of which device (simulator/helicopter) the pilots were flying.

These results lead us to conclude that the computerized measurement scheme, which was analogous in the simulator and in the helicopter, provided a dependable way in which to measure pilot performance. It is concluded that computerized measurement of pilot performance is: 1) sensitive to potentially dangerous flight control degradations, 2) comparable from one type of flight platform to another, and 3) consistent across time. These findings clearly support the continued use and refinement of computerized pilot performance evaluation systems in research. Additionally, the deployment of similar systems in the operational environment seems both feasible and useful. At present, newer portable computerized systems are being evaluated for this type of research and operational use.

References

1. Lees, M. A., and Ellingstad, V. S. 1990. Assessing human performance during the operation of dynamic vehicles: A literature review and examination of methods. Fort Rucker, AL: Western Communications, Inc. Contractor Report. U. S. Army Aeromedical Research Laboratory. USAARL technical report in press.

2. Anastasi, A. 1976. Psychological testing (4th ed.). New York: Macmillan Publishing Co.

3. Simmons, R. R., Caldwell, J. A., Stephens, R. L., Stone. L. W., Carter, D. J., Behar, I., Mitchell, G. W., Knox, F. S., Jones, H. D., and Taylor, P. L., 1989. Effects of the chemical defense antidote atropine sulfate on helicopter pilot performance: A simulator study. Fort Rucker, AL: U. S. Army Aeromedical Research Laboratory. USAARL Report No. 89-17.

4. Caldwell, J. A., Carter, D. J., Stephens, R. L., Delrie, D. M., Stone, L. W., Pearson, J. Y., Pearson, N. R., 1990. Effects of the chemical defense antidote atropine sulfate on helicopter pilot performance: An in-flight study. Fort Rucker, AL, U.S. Army Aeromedical Research Laboratory Technical report in press.

5. Jones, H. D., and Higdon, A. A. 1985. UH-1 simulator data acquisition and management on the USAARL VAX 11-780. Fort Rucker, AL: U. S. Army Aeromedical Research Laboratory. Internal working document.

6. Mitchell, A., Lewis, A., Jones, H., Higdon, A., and Baer, D. 1988. Aircraft in-flight monitoring system (AIMS). Fort Rucker, AL: U. S. Army Aeromedical Research Laboratory. USAARL LR 88-12-5-2.

7. Dixon, W. J., Brown, M. B., Engleman. L., Frane, J. W., Hill, M. A., Jennrich, R. I., and Toporek, J. D. (eds). 1983. BMDP statistical software. Berkeley: University of California Press.

Table 1

Maneuvers and measures used in the combined data set

Maneuver	Measures	Time from dose Simulator	Time from dose Aircraft
Climbing turn	AS, VS	00:37 05:21	00:52 (a.m.) 06:16 (p.m.)
Descending turn	AS, VS	00:39 05:23	00:45 (a.m.) 06:10 (p.m.)
Straight and level	AS, VS, HDG, ALT	01:10 05:54	01:52 (a.m.) 07:11 (p.m.)
ILS approach	AS, LOC, GS	01:41 06:24	02:03 (a.m.) 07:26 (p.m.)

Figure 1
Straight and level

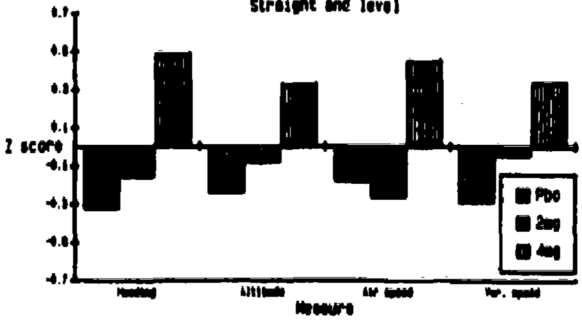


Figure 2
Straight and level air speed

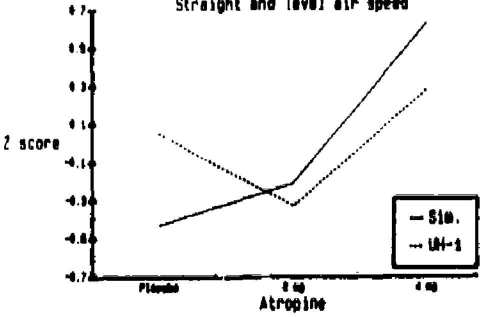


Figure 3
Straight and level vertical speed

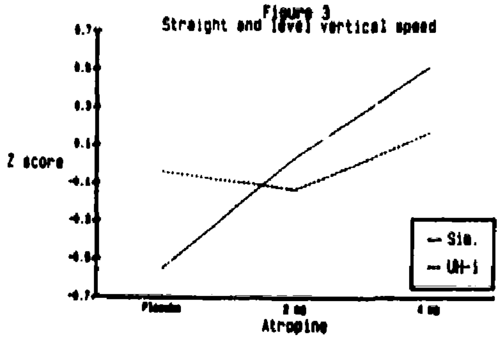


Figure 4
Straight and level altitude

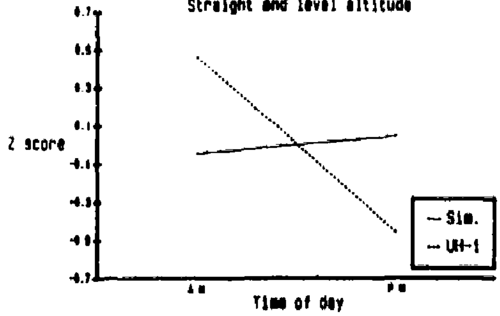


Figure 5
Straight and level air speed

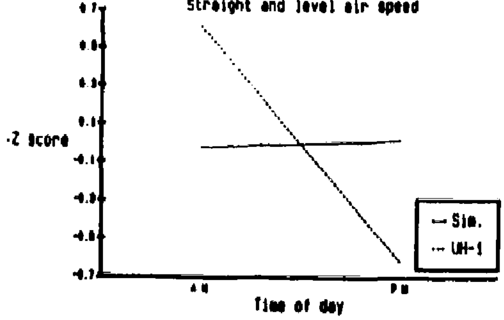


Figure 6
Straight and level vertical speed

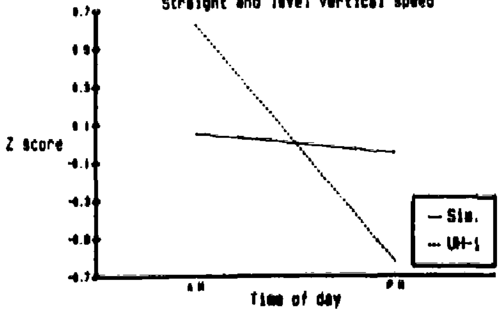


Figure 7
Straight and level heading

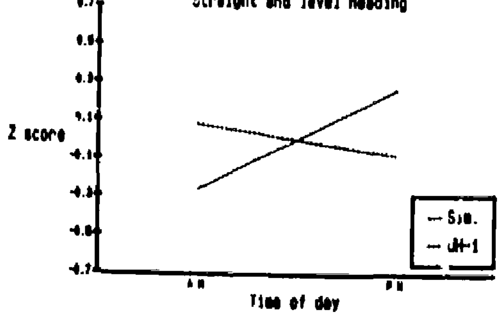


Figure 8
Climbing turn air speed

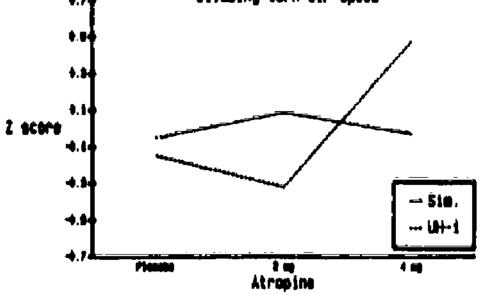


Figure 9
Climbing turn vertical speed

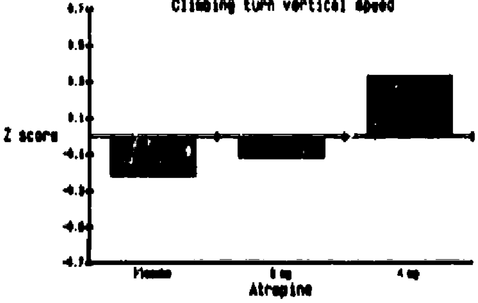


Figure 10
Climbing turn vertical speed

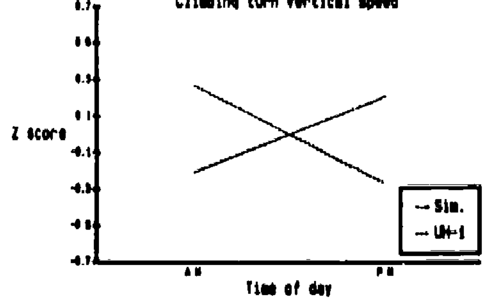


Figure 11
Descending turn air speed

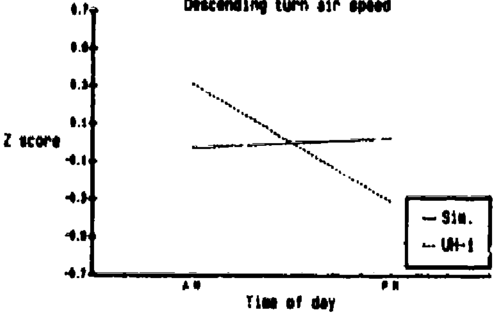


Figure 12
Descending turn vertical speed

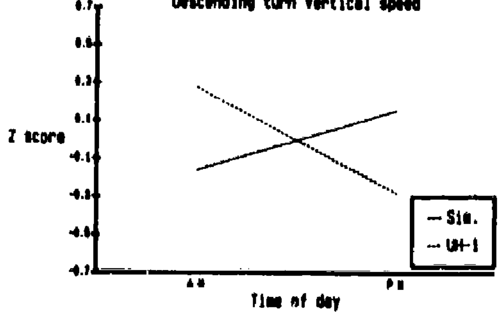


Figure 13
Instrument landing system

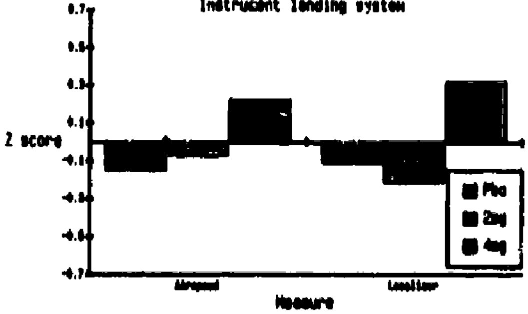
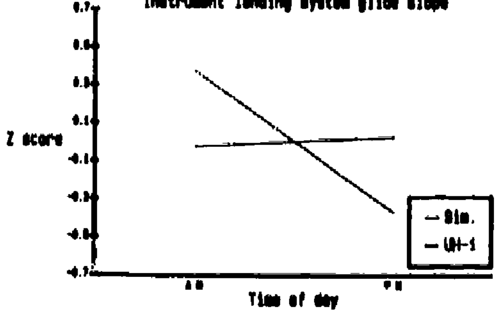


Figure 14
Instrument landing system glide slope



EEG Indicators of Mental Workload : Conceptual and Practical Issues in the Development of a Measurement Tool

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SUMMARY

A first objective in the development of a pilot state monitor is the development of a laboratory tool capable of measuring mental workload. Several general performance 'benchmarks' are identified that facilitate the evaluation of such techniques and a recent programme of research is described and assessed in the light of these criteria.

1. INTRODUCTION

The mental workload of the military aircraft pilot has increased as aircraft have become more complex and as flight and operational envelopes have expanded. This phenomenon has been exacerbated by the increasing emphasis on monitoring and decision-making within the pilot's range of duties. The move towards single crew multi-role military aircraft with enhanced sensor and communications capabilities will increase the likelihood that the pilot will become overloaded with information and unable to perform critical decision-making tasks whilst managing the aircraft systems.

Over the past ten years several psychophysiological measures have been investigated in the search for an objective tool that will help predict or detect performance degradations due to cognitive overload. A longer term aim and the goal of many such programmes is to achieve a real time, online mental workload assessment capability. In due course, this may open the way for features such as dynamic 'reallocation of function' and 'pilot state-monitoring' to be integrated within a 'pilot safety network' in the cockpit.

Much work has specifically investigated the relationship between the electrical activity of the cerebral cortex and human information processing activities.

This paper considers certain performance standards that must be met before electroencephalographic (EEG) measures of mental workload can be usefully integrated within a 'pilot safety network'. The paper concludes with an evaluation of a recent EEG research programme in the light of these requirements.

2. THE CONCEPT OF A SAFETY NETWORK

In the late 1970's there was a halt and down turn to the trend of installing increasing numbers of controls and displays in the cockpit. Since this period both the physical and human sciences have engaged in research with two related aims: (i) to understand and subsequently enhance the pilot-aircraft interface in the cockpit and (ii) to fully exploit the natural capabilities of the pilot. Developments such as the wide angle collimated head-up display; multifunction 'soft' displays; head-movement slaved target designation systems and synthesised speech warnings bear witness to the effectiveness of applying human factors techniques to the integration of crew systems support technologies.

Optimisation of the man-machine interface has become a requirement for all crew systems integration and a philosophy that will endure while the pilot remains physically stationed in the aircraft cockpit.

Further exploitation of the pilot's capabilities will be demonstrated in the coming decade by the introduction of high technology items such as eye-point directed target designation systems, tolerant direct voice input/output systems, 3D auditory threat displays and low technology items such as high angle inclined pilot seating (designed to increase 'G' tolerance).

The next 'wave' of crew systems technology integration lies further in the future. This will allow a profound shift in emphasis to take place within the conventional man/machine relationship. This shift will enable the onboard aircraft systems to monitor the psychological and physiological state of the pilot and to 'act' when the results of these diagnoses exceed normal or acceptable limits. The function of such systems will be twofold: (i) to detect performance degradations arising due to cognitive factors such as mental overload and extreme spatial disorientation and (ii) to detect pilot incapacitation arising from factors such as 'G Induced Loss of Consciousness' (G-LOC), retinal laser damage and other combat injury. A driving factor in this research is the belief that the pilot is (or will be) unable to usefully indicate to the aircraft systems his physiological or psychological state.

It is envisaged that following detection of performance degradations or incapacitation the aircraft systems will assume 'graceful' and fluid control of some or all of the pilot's duties. These concepts are integral to that of the safety network.

It may be a little premature to direct attention to the problems of safety network integration, especially as it is not yet possible to reliably sense, detect and diagnose certain physiological and practically all psychological states.

The biggest challenge facing the development of a safety network system lies in the sensing and diagnosis of psychological state changes associated with mental overload. Physiological and gross psychological state changes (such as blackout) may be detected through the use of existing knowledge and technologies (e.g. electrocardiogram, blood pressure and respiration monitors), but it is not yet equally possible to reliably identify mental workload states. Research into the psychophysiological correlates of mental workload is still at a fundamental level [1,2] and robust, acceptable bio-sensor technologies are under development.

3. SAFETY NETWORK : PSYCHOPHYSIOLOGICAL CRITERIA

The performance and safety problems that may affect the pilot during high levels of mental workload are considered at length in the literature [e.g. 3]. Given the need for a safety network, a major research requirement is to identify robust psychophysiological correlates that can reliably index mental workload states, particularly those states that point to approaching or actual performance breakdowns.

3.1 The Requirement

A tool is needed that will enable researchers to identify pilot mental workload state in relation to a known mental workload 'overload' or 'ceiling' state.

Several research programmes have identified EEG activity as a promising indicator of mental workload and have pointed to this as a possible basis for such a tool. The type of activities that have been investigated in this context range from straightforward frequency recordings to the collection of event related potentials [4,5,6]. Although encouraging results have been reported, the research does not yet appear to be sufficiently mature to support the integration of EEG based technology in the operational cockpit.

It appears likely that no one 'type' of EEG activity will be able to provide an adequate index of mental workload but rather that numerous EEG data sources will prove to be the only way to gain a comprehensive 'picture'. Currently, research is aimed at validating these measures in both the air and in the simulator [4,7].

3.2 Performance Benchmarks

Apart from the identification of workload ceilings there is a need to identify other performance criteria by which the effectiveness and usefulness of a workload measurement tool can be judged. It is suggested that the following criteria represent the minimum performance requirements of such a system. These criteria are derived from the recommendations of several researchers in the field [e.g. 8].

Sensitivity - The sensitivity of a tool refers to its capability to discriminate effectively between mental workload states. For example, although there are many event related potential studies that have found P300 amplitude and latency changes that are sensitive to variations in mental workload demand [9,7] in simple tasks, it is not clear whether this potential is able to index actual or approaching overload 'ceilings' or provide meaningful measurements during complex tasks. These requirements will be essential in the military cockpit. The sensitivity of such a tool will ultimately determine its utility.

Diagnosticity - The diagnosticity of a tool refers to its capability to discriminate between the types of workload demand that contribute to a given mental state. Whether or not this is important will depend upon the proposed function of a safety network. If a smooth and 'graceful' reallocation of function between pilot and aircraft is a goal, then it may be necessary to determine the nature of the problem so that appropriate functions can be reallocated. If purely 'global' measures of workload are required then the measures that are currently being investigated may be adequate as these appear to respond to changes in mental workload state as if it were a unidimensional phenomenon.

Selectivity - The selectivity of a tool determines its capability to respond solely to mental workload state changes and not to changes in other variables such as fatigue and emotional stress. For example, there are several reports claiming that EEG frequency is highly correlated with task complexity [10], however frequency is also associated with variations in fatigue and wakefulness. Clearly any tool based upon frequency must be able to discriminate <u>selectively</u> between frequency changes that are driven by task complexity and changes that are driven by variations in arousal, otherwise it is of little operational value.

Implementation Requirements - Ease of implementing a safety network is critical to its success. Bio-sensors that are uncomfortable, liable to either displacement or electrical noise interference will not be acceptable in the operational environment. Likewise lengthy preflight instrumentation, calibration and fitting will also reduce the likelihood that such technology will be accepted within the cockpit.

Reliability - This requirement simply underscores the need for all the above criteria to be met with a high degree of reliability. If pilots don't trust safety network systems they will oppose their integration and turn them off.

4. EEG RESEARCH PROGRAMME EVALUATION

In 1986, a programme of collaborative research[1] was launched with the aim of identifying robust EEG indicators of mental workload. Particular emphasis was paid to the existence of slow EEG potential shifts that appeared to be in some way associated with variations in task difficulty. Whilst this programme has met with both success and setback, progress has been made towards the development of a tool capable of indexing mental state. This section summarises the development of this research with reference to the performance benchmark criteria proposed earlier in the paper.

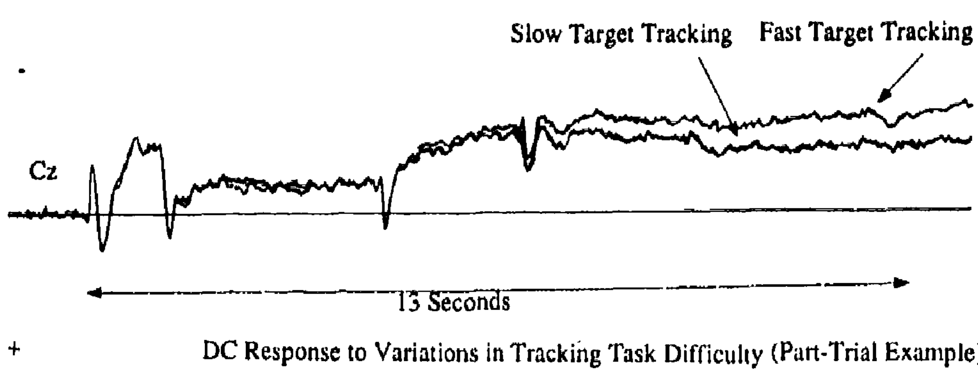
4.1 Phase I

Results of the Phase I study indicated that the slow potential shifts (or 'DC' shifts as they became known due to the data gathering technique), appeared directly related to task difficulty. Increases in tracking task difficulty appeared to directly result in increases in waveform negativity (Figure 1). Interestingly, the DC shift response to variations in the difficulty of a short-term memory task (a Sternberg task [14] with varying positive set size) differed from that of the tracking task in that the greater the demand the less negative the DC shift (Figure 2).

As has been frequently reported in the literature [e.g. 6,9], ERP P300 amplitudes were found to decrease with increasing task demands.

Although the task (simulated missile engagement) was relatively simple to perform, it was more difficult to analyze and link specific changes in task demand to changes in EEG activity. This occurred because the 28 second task contained several different

Figure 1



DC Response to Variations in Tracking Task Difficulty (Part-Trial Example)
(Fast Targets/Slow Targets)

sub-tasks including those of visual and manual tracking (varying in speed and perturbation), decision making and memorisation, and some of these tasks ran concurrently with other tasks. Interpretation was further confounded by the high levels of statistical significance found between EEG activities and almost all dependent variables.

Consequently, apart from the very clear ERP and DC shift differences observed during the short-term memory task, it was not possible to identify exactly the underlying cause of many of the changes in the EEG waveform. However on the basis of the differences observed between EEG activities and task condition there did appear to be grounds for continuing the research and further examining the DC shift phenomenon.

Unsurprisingly, at this stage in the research none of the performance benchmarks proposed earlier in the paper had been achieved.

1. Undertaken between BAe, Sowerby Research Centre and the Burden Neurological Institute, Bristol.

4.2 Phase II

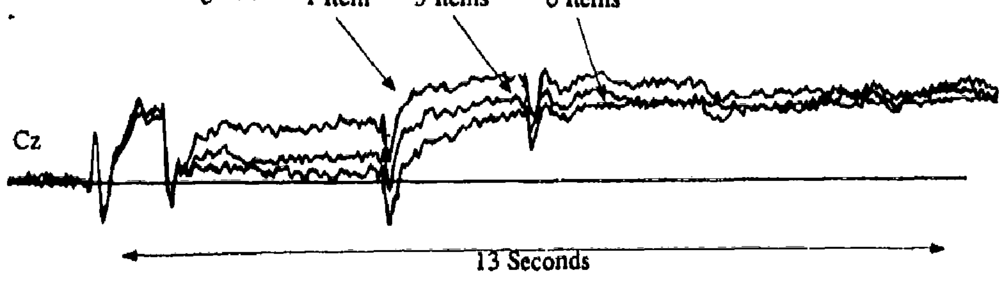
Phase II [15] was developed with the intention of evaluating (i) the selectivity and (ii) the sensitivity of the effects that had been observed.

It was concluded that either the tracking or memory elements (or both) of the Pnase I task were related to the observed variations in DC shift. Two experiments were designed to independently address the effects of variations in both memory and tracking demand:

(i) The memory or 'cognitive' task were designed to place selective demands upon the storage and manipulative processes associated with a limited capacity working memory [16]. It was intended not only to replicate the type of demand observed during the memory task in Phase I but also to assess the sensitivity of the DC response by increasing task demand to a point at which performance would break down. This was done to determine whether or not a ceiling effect could be found in the EEG DC shift.

(ii) The tracking task was designed to place several levels of task difficulty selectively upon those motor processes associated with tracking. It was intended to examine sensitivity by forcing task difficulty to the point of breakdown.

Figure 2



DC Response to Variations in Memory Demand (Part-Trial Example)
(Number of Items Held in Memory)

Surprisingly, upon analysis neither the cognitive nor the tracking task difficulty manipulations could be found statistically related to changes in EEG DC waveform, although the task difficulty variations were accompanied by significant differences in performance.

Cognitive task ERP P300 amplitudes were found to distinguish between target and non-target items as well as between difficulty conditions (Figure 3). Interestingly, it was noted that over all Phase I and II tasks a positive going DC shift could be observed when task relevant visual information was presented at the start of each trial (Figure 4).

Performance varied in both Phase II tasks roughly according to task difficulty condition. In the working memory task these variations were also supported by P300 amplitude changes. The results of Phase II indicated that DC negative shifts did not appear to be related to simple increases in tracking difficulty or in working memory demand.

As the Phase II task conditions were harder than in Phase I it could be argued that the Phase II task conditions were outside of the sensitivity band of the DC negative shift.

Thus it was not clear whether the DC negative shifts observed in Phase I were (i) connected with aspects of the Phase I task that were not present in Phase II, (ii) related to some non task-related differences between the Phase I tasks (e.g. emotional responses) or (iii) entirely artefactual.

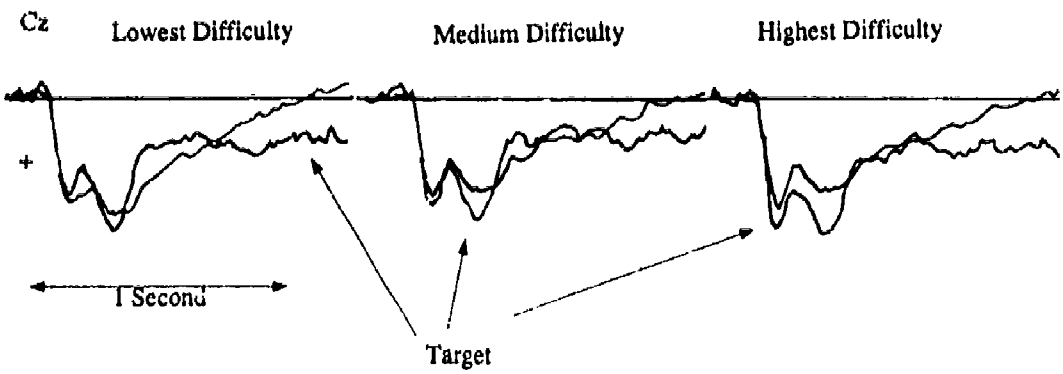
After studying the results of Phase II in some detail it was postulated that the 'DC' producing element present in Phase I but missing in Phase II may be related to factors such as: 'tas' relevance', 'involvement', 'salience' or 'engagement'. This hypothesis was slightly supported by the observation that positive going DC shifts were consistently observed in both Phase I and Phase II during the first period of each trial over those periods when task relevant information was presented (Figure 4).

At this point in the research none of the performance benchmark criteria referred to earlier had been met to any useful degree, although it had been found that DC negative shifts did not respond to variations in tracking and memory demand difficulty when these tasks were undertaken in isolation.

4.3 Phase III

A third study was designed with the aim of replicating the DC shift differences observed during the Phase I study, but under more controlled task conditions than in Phase I and with a more realistic, 'engaging' and salient task than in Phase II. The task was designed to minimise purely 'motor' elements and to enhance the cognitive elements associated with visual monitoring of displayed information - the sub-task element during which consistent DC negative shift variations had been observed in Phase I and Phase II. The task was also designed to overcome a repeated single trial paradigm so that a constant, uninterrupted level of task involvement could be maintained over the whole experimental period.

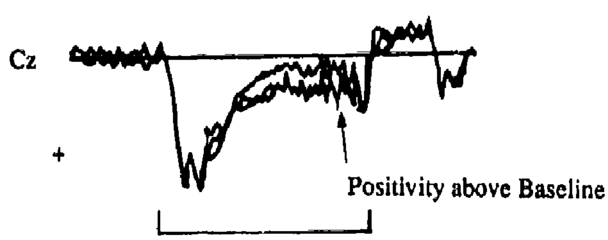
Figure 3



ERP Variations with (i) Running Memory Task Difficulty
(ii) Target / Non-Target Conditions

The task required the subject to monitor a number of moving gauges that simulated changes in a hypothetical system's status and to respond when readings exceeded certain limits. The experiment manipulated a variable related to the perceived likelihood of the system exceeding these limits, the psychological corollary of which may be a variation in attentional demand, but not necessarily in task difficulty.

Figure 4



Apparent DC Shift Response during Presentation
of Task Relevant Visual Information

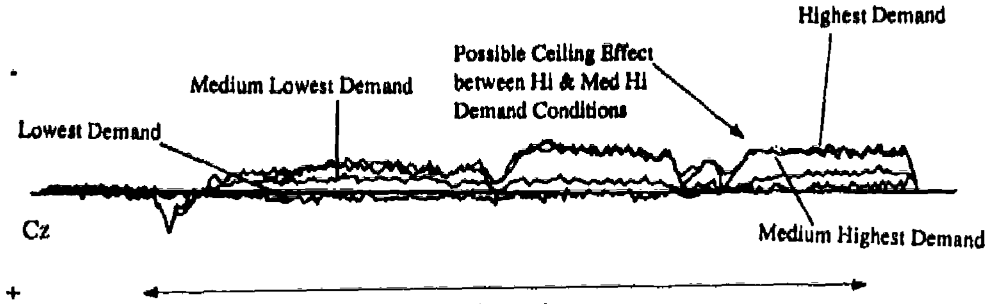
Results of the experiment [17] were encouraging. DC negative shifts varied significantly according to most manipulations in task variables, apparently indexing task related differences (Figure 5). Three out of the four levels of task demand were significantly dissociated demonstrating that DC shifts are not simply two-state (on/off) indicators of variations in attentional demand but that they also appear to hold some level of sensitivity to incremental variations in attentional demand. Phase III results indicate that the selectivity of the DC negative shift may be quite high. Although speculative, the diagnosticity of the tool does appear to be less related to an 'information processing' view of workload than to a nebulous collection of psychological variables including those of task salience, task involvement and an integration of the factors of controlled processing [18] and focused visual attention. The lack of DC shift difference observed between the two most demanding levels may be a preliminary indication of a low ceiling of sensitivity (see Figure 5).

4.4 Phase IV

Phase IV was designed to further address the issue of sensitivity. A similar paradigm to that employed at Phase III was developed but with a greater emphasis placed upon overloading the subject. This was done to force a breakdown in performance so that concurrent DC shift activity could be observed.

Although this experimental work is still ongoing, interim analysis of results indicates that there is a clear DC shift dissociation between task variations. However, it has not yet been possible to evaluate the DC shift correlates of performance

Figure 5



DC Shift Response during Variations in Focused Attentional Demand

breakdown as some subjects have coped with the highest difficulty levels whilst others have not. It is important that these groups are analysed separately and as yet too few subjects have been run to make this worthwhile.

5. CONCLUSION

To date the research programme has progressed steadily towards the goals inherent in the performance benchmark criteria. Perhaps oddly, the programme has identified task conditions that appear to be reliably associated with variations in the slow potential termed the DC negative shift whilst the underlying task-related cause of these variations is still obscure. However, it does appear that the observed variations may be quantitatively related to several factors including that of focused visual attention.

It would appear that as with other potential EEG measurement tools, DC negative shifts may eventually provide a unique perspective upon the mental workload problem, rather than a comprehensive view.

Before this potential measurement tool can be employed in the laboratory or deployed within an operational safety network it must be established that (i) the task-related 'cause' of variations in DC shift response are selectively and diagnostically linked to attentional processes and (ii) that the sensitivity response of the DC shift is sufficiently broad to encompass performance breakdown without hitting a response ceiling.

It is proposed that similar psychophysiological techniques are evaluated with reference to the 'performance benchmark criteria' so that a degree of correspondence is achieved in the assessment of developing 'safety network' tools.

6. REFERENCES AND BIBLIOGRAPHY

1. AGARD-CP-432 "Electrical and Magnetic Activity of the Central Nervous System: Research and Clinical Applications in Aerospace Medicine" 1987.

2. NASA-CP-2504 "Mental-State Estimation" 1987.

3. Wiener, E.L.; Nagel, D.C., "Human Factors in Aviation" Academic Press Inc. (London) Ltd. 1988 ISBN 0-1-750030-8.

4. Sterman, M.B.; Schummer, G.J.; Dushenko, T.W.; Smith, J.C., "Electroencephalographic Correlates of Pilot Performance: Simulation and In-Flight Studies" AGARD, Electric and Magnetic Activity of the Central Nervous System: Research and Clinical Applications in Aerospace Medicine 1987.

5. Moise, S.L. Jnr., 1985 "Investigation of the Use of Steady State Evoked Potentials for Human Performance and Workload Assessment and Control" Nova Technical, Inc., Tarzana, CA. Air Force Office of Scientific Research, Bolling AFB, DC. Final Technical Report.

6. Lindholm, E.; Cheatham, C.; Koriath, J.; Longbridge, T.M., 1984 "Physiological Assessment of Aircraft Pilot Workload in Simulated Landing and Simulated Hostile Threat Environment" Air Force Human Resources Lab., Brooks AFB, TX. Final Report.

7. Horst, R.L.; Mahaffey, D.L.; Munson, R.C., 1989 "Brain-Wave Measures of Workload in Advanced Cockpits: The Transition of Technology for Laboratory to Cockpit Simulator, Phase II" Advanced Resources Development Corp., Col., - NASA, Washington, DC. Final Report.

8. Sheridan, T.; Stassen, H., 1979 "Definitions, Models and Measures of Mental Workload" In Moray, N. (ed.) "Mental Workload Its Theory and Measurement" NY, Plenum Press.

9. Isreal, J.B.; Wickens, C.D.; Chesney, G.L.; Donchin, E., 1980 "The Event-Related Brain Potential as an Index of Display Monitoring Workload" Human Factors, 2, pp.214-17.

10. Bagrova, N.D.; Korobov, R.N.; Gromov, IU.M., 1984 "The Information Content of EEG Data in Predicting Operator Work Capacity" Fiziologiia Cheloveka, Vol.10, pp.41-46.

11. Miller, J.J.; Van Treuren, J.; McPherson, B.W., 1989 "Biocybernetic Related Applications Involving Neural Networks" AIAA Conference Paper 89-3092, pp.811-818.

12. Puzey, N.J., 1990 "Use of Physiological Indicators for Automatic Recognition of Human Mental States" British Aerospace, Sowerby Research Centre Tech. Report, TM AIP011.

13. McCallum, W.C.; Cooper, R.; Pocock, P.V., 1988 "Event Related and Steady Potential Changes in the Brain Related to Workload During Tracking" In AGARD-CP-432 "Electrical and Magnetic Activity of the Central Nervous System: Research and Clinical Applications in Aerospace Medicine".

14. Sternberg, S., 1975 "Memory Scanning: New Findings and Current Controversies" Q.J. Exp. Psych., 27:1-32,106.

15. McCallum, W.C., "Brain Indicators of Mental Load" 1987, Burden Neurological Institute Report for BAe, SRC.

16. Baddeley, A.D.; Hitch, G.J., 1974 "Working Memory" In Recent Advances in Learning and Motivation, Vol.VIII (G. Bower, ed.) pp.47-90, Academic Press, New York.

17. McCallum, W.C., "Brain Indicators of Mental Load: DC Shifts Associated with Monitoring a Visual Display" 1988, Burden Neurological Institute Report for BAe, SRC.

18. Shiffrin & Schneider, 1977 "Controlled and Automatic Human Information Processing: Perceptual Learning, Automatic Attending, and a General Theory" Psychological Review, 84, 119-127.

OPTIMISATION OF OPERATIONAL WORKLOAD LEVELS USING NEUROPHYSIOLOGICAL AND COGNITIVE TECHNIQUES

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SUMMARY

The object of the research programme at RAE is to identify and assess extremes of operational workload using either existing measures, for example, NASA TLX, SWAT, etc together with Neurological measurements. Data already exists from specialist laboratories which shows a reliable increase in the DC levels of brain activity with increasing workloads.

In order to optimise workloads, the objectives of future missions will be predicted and analysed. Following this detailed task analysis, timeline analysis and attentional demand analysis will be used to identify the extent to which particular cognitive channels, eg visual, auditory, and psychomotor are being used at any one time. In parallel with this analysis evoked response techniques will be developed from the laboratory studies towards man-mountable apparatus for in-flight use. This will require the development of low noise electrically isolated DC amplifiers of high dynamic range design to obtain physiological data from the man with the minimum of operator support.

In recognising that at high workload levels, there is a strong possibility of subjects ignoring secondary tasks during laboratory trials, the aim will be to provide a high degree of perceived realism in laboratory tasks. To achieve this aim a low-cost, microcomputer based flight/combat simulator is under development to allow tasks of variable complexity to be fully integrated into an ensemble that is perceived by subjects as realistic.

From these analyses areas of task conflict and work overload can be predicted with the aim of assimilating the total workload to a consistent optimal level throughout the mission. Optimisation will be achieved either by presenting a more even distribution of tasks, or by reassessing tasks so as not to overload any one channel at any one time.

INTRODUCTION

In both civil and military flying a major cause of performance degradation is the existence of periods of excessive workload when the operator is faced with demands on his processing abilities which simply cannot be fully met, no matter what the effort he is capable of applying.

Workload has been defined in many ways; as "the cost incurred by the human operator in achieving a particular level of performance" (1), "the operator's evaluation of the attentional load margin (between their motivated capacity and the current task demands) while achieving adequate task performance in a mission-relevant context" (2), or even as " .... a hypothetical construct that reflects the interaction between a specific individual and the demands imposed by a specific task" (3).

However workload is defined, for practical purposes it is often useful to consider it as one of the stressors imposed on the operator, and, to extend the mechanical analogy, the resultant strain as being the effect on the operator's performance.

THE PERCEIVED PROBLEM

Workload demands may arise from a variety of sources or may be the result of a concerted demand on just one processing modality, such as may occur when aircrew are required to deal with incoming and outgoing communications with a number of other units, or are required to monitor and read displays while observing the terrain outside the aircraft and simultaneously reading a map.

Dealing with workload peaks by using a variety of ergonomic techniques including enhancement of the man-machine interface, redistribution of tasks between crew members and, in the future, applying artificial intelligence to support the human operators' capacity depends critically on identification of the precise source of the overload and how it affects the processing abilities of the operator. Workload assessment is most often of two types; subjective or objective, Figure 1.

SUBJECTIVE WORKLOAD

The subjective type, in which data from carefully structured questionnaires and interviews with operators of the aircraft, (or of a similar aircraft or system to that under development), are analysed and integrated to give an overall picture of the subjective demands of the tasks for different mission types.

Probably still the most widely used of this type of assessment is the Cooper-Harper scale and its modifications. Designed originally as a technique for assessing aircraft handling qualities using a ten-point scale derived from a decision tree, it has been used in a modified form as a means of assessing workload.

The SWAT technique is also widely used for a variety of purposes; three aspects of workload, temporal effort, mental effort and stress are rated on a three-point scale, and subjects are then asked to rank order all 27 possible combinations so that the model they use can be determined, and an interval scale developed using a conjoint scaling technique.

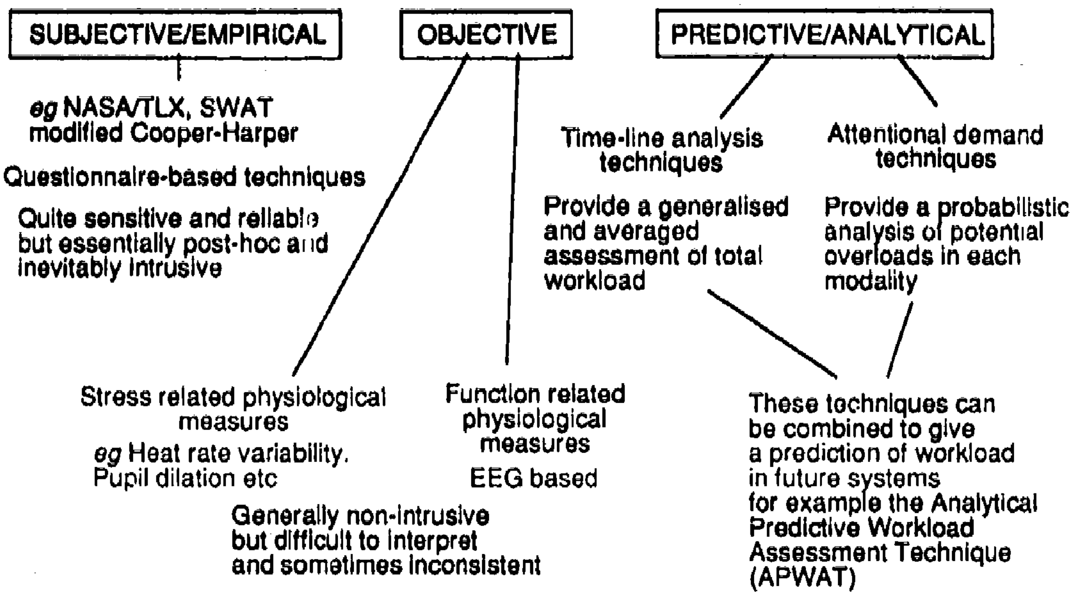

Figure 1 Techniques Of Workload Assessment

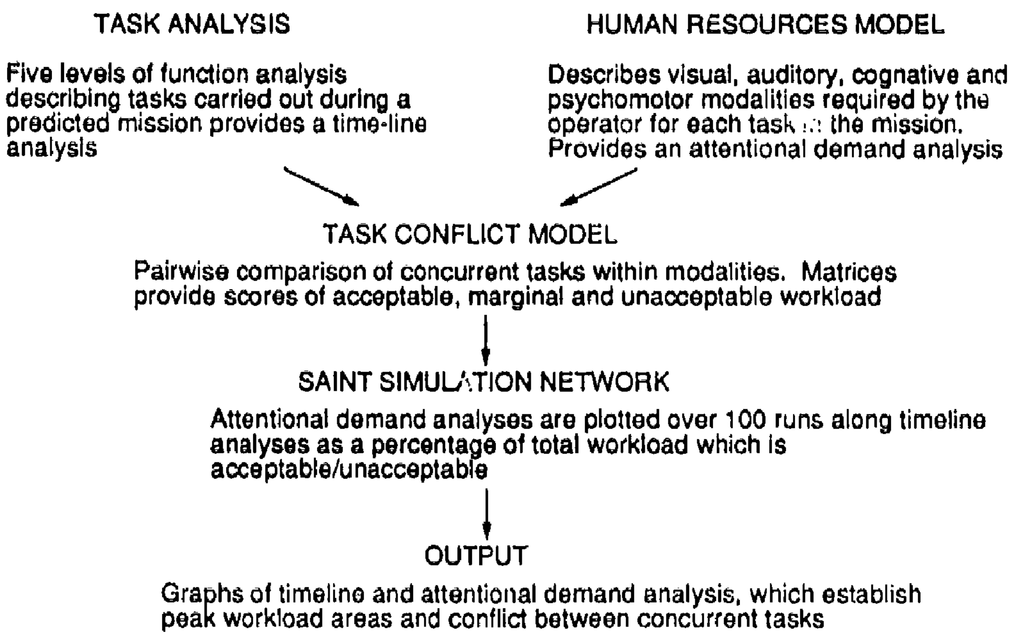

Figure 2 Summary Of Analytical Predictive Workload Assessment Technique

NASA Ames have developed their Task Load Index (TLX) technique which has some similarities to the SWAT system. The TLX system is based on six sub-scales consisting of mental, physical and temporal demands, and the subjects' assessment of their own effort, frustration and performance. TLX also uses a conjoint scaling technique in which the subjects make pairwise comparisons of the six factors which allow comparative weightings to be established for a particular task, and then rate the magnitude of that factor between 'low and high' on a 12 cm line.

OBJECTIVE WORKLOAD

Alternatively to these essentially subjective techniques, or as a part of a combined test battery, a variety of objective physiological techniques can be used. In addition to the neurological methods described in this paper, objective measures such as heart rate and variability, eye-blink rate and even auditory canal temperature have been used to give a relatively non-intrusive (but not always totally reliable) workload assessment, which has the advantage that it can be made concurrent with the performance of the flying task.

EVOKED RESPONSES

Evoked response, or event related potential, techniques, involving studies of brain electrical activity immediately following a stimulus, have been gaining credibility in recent years as a means of studying information processing and cognitive activity within the brain (4,5,6,7). Advances in the technology have led to a considerable expansion in the application of these techniques to studies aimed at identifying various components in brain activity during the performance of a wide range of laboratory tasks.

Possibly the greatest increase in applications has been in the area of mental workload. As operators of systems of all kinds are encountering an increase in the ratio of mental to physical workload, it is becoming increasingly desirable for designers of systems to be able to define the performance envelope of operators. The endogenous components of event related brain activity, particularly P300, have been used to explore the allocation of 'resources' within the brain during task performance.

Work using dual-task paradigms (8,9,10) has shown resource reciprocity. As primary task load increased the primary task P300 also increased as more resources were allocated to that task and away from the secondary task, where a corresponding decrease in P300 level was observed. Other workers (11,12,13,14,15) have related features of P300 and other early signal components to workload factors.

The signals in the work described above, all occur within a few hundred milliseconds of the eliciting event. However, changes in EEG activity have been observed over much longer periods. Slowly changing DC levels have been noted which have been connected with levels of arousal or activity (16). In particular a slow potential change known as the Contingent Negative Variation has been shown to be associated with changes in attention, motivation, anticipation and task complexity.

It is the last of these which is of interest to the programme discussed here. Data are already available (17) which show reliable increases in DC levels of evoked potentials with increasing workload.

These techniques are currently restricted to laboratory applications. However, by focusing effort solely on the characterisation of workload, in particular, the identification of approaching excess workload, and, improving the technology involved, RAE intend to progress towards a man-mountable apparatus for in-flight use.

In the past research into human performance and workload has suffered from two main problems: the lack of relevance of laboratory produced data to current practical problems and the lack of a reliable measure of workload. The work programme proposed at the Royal Aerospace Establishment (RAE) is aimed at solving both problems by a series of research tasks including both the physiological and psychological aspects of workload.

REQUIREMENTS FOR NEUROPHYSIOLOGICAL MONITORING

To attempt to measure brain activity several specific problems must be addressed to ensure good electrical signals under conditions of absolute safety. This last factor is of paramount importance as the introduction of any unwanted electrical signals into the brain would be counter productive to the survival of the pilot, the very thing that the workload study is supposed to improve. The design of any head amplifier must therefore, meet the following specification for electrical safety and measurement in a non-obtrusive fashion.

INPUT AMPLIFIER SPECIFICATION

Differential input, single ended output Power by isolation power supply (1000V protection)
Gain switchable between 10 or 100
Input noise <1uV pp (.1 Hz-100 Hz) <2uV pp (.1 Hz-100 Hz)
DC stability <1 uV/hr
Thermal range -10 to 30°C
Low thermal drift (as small as possible)
Low input bias current <10 pA
High input impedance >10000 Mn
High CMR >100 dB
Bandwidth DC to 10 KHz
Dynamic range ± 10 Volts

Such an amplifier is under development by the RAE in collaboration with the Burden Institute for both a laboratory multi-channel research instrument and flyable pilot monitoring system.

PROPOSED COGNITIVE RESEARCH PROGRAMME

Although present techniques are very useful in the assessment of current systems, their value in equipment procurement, where the possible performance of a system for its operators must be predicted at a very early stage, is limited by the extent to which subjective assessment by expert operators of an In-Service aircraft or system can be extrapolated to what may be a totally new concept. What is needed is a predictive-analytical workload assessment technique which can, given the anticipated missile profiles, analyse the workload demands made on the operator throughout the mission, both quantitatively, and, most importantly, qualitatively. Such a predictive technique has to have the ability to incorporate probabilistic data into a detailed task analysis from which a model of the predicted moment-to-moment demands on the operator's processing capacity can be made, together with an analysis of the modality or modalities which are under pressure.

At RAE Farnborough we are developing such a predictive-analytical system for use initially as a procurement tool for assessment both of developed aircraft and systems which are under consideration for procurement, and as a direct aid in the development of new concepts.

The aim is to predict areas of high workload during a mission using a technique developed by McCracken and Aldrich (18), and then apply some of the existing measures such as NASA TLX and SWAT, in order to validate the model. The predictive technique has its advantages in that:

1 it is a probabilistic model,
2 it follows a top-down process,
3 it looks at the mission as a whole, and not at specifically selected tasks,
4 it includes both timeline and attentional demand analyses.

The timeline analysis is required to see what proportion of any one mission the operator spends on any one task and the attentional demand analysis is required in order to determine which modalities the human uses to carry out each task.

This predictive technique (Figure 2) involves analysing the expected mission profile for the particular aircraft, and the physiological and psychological aspects of carrying out the mission and then to see where the areas of task conflict lie. Consequently it is split into three parts, the task analysis, a human resources model, and a task conflict model, which ties together the first two sections.

Initially, there are five levels to the task analysis. The first level indicates the major functions to be performed to complete the mission and then levels two and three break these functions down into further functions. A fourth level provides the information requirements and initiating conditions and a fifth level of tasks required is made. For each of the tasks it has to be decided whether they are better done by man or machine and then a task description is written.

The human resources model is then looked at to see which modalities are used for each task. From the McCracken and Aldrich model there are four modalities used, visual, auditory, cognitive and psychomotor (commonly known as VACPs). The visual, cognitive and psychomotor modalities each have seven descriptors, although currently there are only four for the auditory modality. Consequently this does not fall in line with the other scales at present, but a seven point scale for the auditory modality is under development and we hope to implement this as soon as possible. Each descriptor is then allocated a weighting of 1-7 or 1-4 respectively. For each task from the task analysis a VACP is assigned. However, tasks are not all serially placed throughout time during a mission, that is, there are lots of concurrent tasks, some of which lead to very high workload areas and areas of task conflict.

The task conflict model brings together the first two sections and is used to determine whether the concurrent tasks are compatible. By rating one modality of one task along one side of a square and rating the same modality of the concurrent task along the perpendicular side a matrix can be produced for each modality. The corresponding cell of the outcome matrix is then described in one of three ways, acceptable (A), marginal (M) and unacceptable (U), Figure 3 illustrates the Situation Outcome Matrices for the visual and auditory modalities. A simple set of rules is devised in order to determine the overall workload situation for any series of concurrent tasks, for example, if any attentional demand category is unacceptable the situation is unacceptable.

The predictions as to whether two concurrent tasks are acceptable, marginal or unacceptable are carried out by the SAINT Simulation Programme. Prior to simulating the initiation of each task the programme compares the attentional demand rating of the task to be performed against the ratings of ongoing tasks. The outcome of this prediction is then presented in two formats: (1) tabular and (2) graphical. By overlaying the timeline analysis graph on the frequency of occurrence graph it can be seen that for some areas of a mission, where tasks may be very short and simple the pilot can be occupied 100% of the time, but that overload can still occur when only 20% of the time is occupied. Overload on a task may occur just because the outcome matrix of two concurrent tasks show an unacceptable situation either for one particular modality or for the overall situation due to the defining rules.

We aim to apply this technique to new proposed aircraft both fixed wing and rotary, as well as to those aircraft currently in service, although the model can be adapted to suit operator workload in other vehicles and situations. By comparing the predictive results with results of other subjective techniques such as NASA TLX and SWAT and physiological measures such as EEG we will be able to validate the model. The technique will then be evolved and adapted as a standard assessment and design tool for aircraft under development and under consideration for procurement.

VISUAL OUTCOME MATRIX

First task *Description*	Rating	**Concurrent task** 1	2	3	4	5	6	7
Monitor, scan, survey	1	A	A	A	A	A	A	M
Detect movement, change in intensity	2	A	A	A	A	A	A	M
Trace, follow track	3	A	A	U	A	M	M	U
Align, aim, orient	4	A	A	A	U	M	M	U
Discriminate on the basis of symbol	5	A	A	M	M	U	U	U
Discriminate on multiple aspects	6	A	A	M	M	U	U	U
Read, decipher text, decode	7	M	M	U	U	U	U	U

AUDITORY OUTCOME MATRIX

First task *Description*	Rating	**Concurrent task** 1	2	3	4
Detect occurrence of sound	1	A	A	A	A
Detect change in amplitude, pitch	2	A	A	M	M
Understand message	3	A	M	U	U
Discriminate signal patterns	4	A	M	U	U

Figure 3 Situation Outcome Matrices

SIMULATED FLIGHT ENVIRONMENT

Recognising that, at the high workload levels to be studied, there is a strong possibility of subjects ignoring secondary tasks during laboratory trials, the aim will be to provide a high degree of perceived realism in laboratory tasks. A low-cost, microcomputer-based, flight/combat simulator is under development. This allows tasks of variable complexity to be fully integrated into an ensemble that is perceived by subjects as realistic.

The system under development is one of a new generation of microprocessor based simulators designed to complement rather than replace high level systems. They are intended to show how an individual will respond under the stress of the activity rather than measure the response when operating a piece of hardware in a controlled environment.

The system comprises a network of nine microprocessors providing in-cockpit controls, instrument displays on four in-cockpit screens, three real-world views and operator control over events occurring within the scenario. A high speed, multi-parallel connection box allows data flow amongst processors sufficient to achieve a refresh rate on all screens of greater than 25 Hz.

Aerodynamic performance, weapon capability and adversary tactical execution are modulled simply using a few basic parameters on the basis of energy manoeuvrability. Threat indicator display and radar performance are modelled in a similar manner, the key feature in all cases being the speed with which reprogramming can be completed. The force ratios, mission scenarios, type of threat and quality of threat can be varied at run time and a spread sheet will give the ability to programme exact performance and operational limits when required. Initially a minimal version of the simulator will be used, configured such that the task to be performed maps closely to a laboratory task used for early work on slow potential and proving of the EEG hardware.

A history of events within the model will be available from the network firstly for synchronising those events with recorded brain activity and secondly for the extraction of subject performance data for analysis.

Following a satisfactory proving period, the ease and speed with which the model may be reprogrammed will allow a series of trials in which the number and complexity of tasks to be performed is gradually increased.

It is planned to define the type of relationship between workload and slow potentials and ERP over a much wider range of workloads, to establish the effects of different categories of workload (visual, cognitive etc) and to establish the behaviour when workload is increased to the point of overload. During this period the subjective workload measurement techniques will be used to quantify the workload at each significant stage and show how the two techniques may be used to complement each other.

REFERENCES

(1) Hart, S.G; "Theoretical basis for workload assessment research at NASA Ames Research Centre. In Proceedings of the Workshop on Flight Testing to Identify Pilot Workload and Pilot Dynamics. AFFTC-TR-82-5, 1982.

(2) Jex, H.R; "Measuring Mental Workload" in "Human Mental Workload", ed P.A. Hancock and N. Meshkati, Elsevier Science 1988.

(3) O'Donnell, R.D; "Historical Foundation of the AFAMRL Workload Programme" in Proceedings of the Workshop on Flight Testing to Identify Pilot Workload and Pilot Dynamics". AFFTC-TR-82 5, 1982.

(4) Ullsberger, P., Neumann, U, Gille, H-G, Pietschmann, M; "P300 component of the ERP as an index of processing difficulty" In Human Memory and Cognitive Capabilities" North-Holland, Amsterdam 723-731 1986.

(5) Ullsberger, P, Metz, A-M, Gille, H-G; "The P300 component of the event related brain potential and mental effort", Ergonomics 31 8 1127-1137 1987.

(6) Donchin, E, Wickens, C; "The event related brain potential as an index of information processing, cognitive activity and skill acquisition" REPT. NO. CPL 85-1 AFOSR TR 85 0662 800pp 1985.

(7) Donchin, E, Wickens, C; "Workload methodology" AGARD (AD45548) Flight Mechanics Panel AGARD-AG-282 ISBN-92-835-1546-3 AGARDograph No 282 1987.

(8) Isreal, J.B, Chesney, G.L, Wickens, C.D, Donchin, E; "P300 and tracking difficulty: Evidence for multiple resources in dual-task performance" Psychophysiology 17 259-272 1980.

(9) Isreal, J.B, Wickens, C.D, Donchin, E; "The dynamics of P300 during dual-task performance" IN Kornhuber, H.H, Deecke, L; (eds) "Motivation, motor and sensory processes of the brain Electric potentials" Pub Amsterdam, Elsevier/NH 416-321 1980.

(10) Kramer, A, Wickens, C.D, Donchin, E; "An analysis of the processing requirements of a complex perceptual-motor task" Human Factors 25 597-621 1983.

(11) Biferno, M.A; "Mental workload measurement: "Event-related potentials and ratings of workload and fatigue" NTIS N85-26139/4/GAR NAS 1.26:177354 NASA-CR-1777354 CON NAS2-11860 23pp 1985.

(12) Trejo, L.J, Lewis, G.W, Blankenship, M.H: Brain activity during tactical decision making. PART 2: Probe evoked potentials and workload" Technical Note AD-A188688 NPRDC-TN-88-12-PT-2 30pp 1986.

(13) O'Donnell, R.D, Wilson, G; "Cortical evoked response and eyeblink measures in the workload evaluation of alternative landing system displays" In: AGARD Practical Assessment of Pilot Workload N87-30054/7 24-54 AD-A184 834 52-55 1987.

(14) Munson, R.C, Horst, R.L, Mahaffey, D.L; "Primary task event-related potentials related to different aspects of information processing" In: NASA Langley Research Center, Mental-state Estimation AD234656 NAS1-17576; NAS1-18019; N88-23370 16-53; NTIS HC A17/MF A01 163-178 1987.

(15) Ossenblok, P, Spekreuse, H; "Visual evoked potentials as indicators of the workload at visual display terminals" Ergonomics 31 10 1437-1448 1988.

(16) McCallum, W.C, Cooper, R, Pocock, P.V; "A study of brain electrical changes associated with increases in operator load in a visual tracking task" Rept on Contract No BU33510 1986.

(17) McCallum, W.C, Cooper, R, Pocock, P.V; "Brain slow potential and ERP changes associated with operator load in a visual tracking task" Electroencephalography and clinical Neurophysiology 69 453-468 1988.

(18) McCracken, J.H, Aldrich, T.B; "Analysis of the selected LHX mission functions", US Army Research Institute, Fort Rucleer Ala 1984.

ETUDE DE LA VIGILANCE DES PILOTES AU COURS DE VOLS LONG-COURRIERS

par

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RESUME
Les variations de l'état d'éveil et de la performance au cours d'activités monotones ont été montrées par de nombreux auteurs. Dans les transports aériens, la monotonie se trouve souvent associée avec des cycles irréguliers de travail et des décalages horaires importants. Les interactions entre ces facteurs contribuent à amplifier la baisse des performances et de la vigilance. Afin d'étudier le comportement des pilotes au cours de vols long-courriers, une recherche a été entreprise. Elle a comme objectif d'identifier les phases d'hypovigilance et d'évaluer leurs répercussions sur la performance des pilotes. La méthode d'étude retenue repose sur une évaluation objective des fluctuations de l'éveil des pilotes à partir de paramètres physiologiques, complétée par une analyse des activités des différents membres de l'équipage. Des techniques ambulatoires sont utilisées pour recueillir l'électro-encéphalogramme (EEG), l'électro-oculogramme (EOG) et l'électrocardiogramme (ECG) au cours des vols. La fréquence cardiaque et l'activité motrice du poignet sont également enregistrées au cours des vols et pendant les périodes de repos. L'activité motrice du poignet permet d'obtenir des informations sur les cycles activités-repos des pilotes. L'observation des activités et de la tâche de l'équipage est réalisée simultanément à ces enregistrements en utilisant une grille codée. Huit vols long-courriers, transméridiens et nord-sud, ont été effectués au cours de la première étape de mises au point des protocoles. Les premiers résultats montrent d'importantes variations dans les spectres d'EEG quantifiés 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 pendant la journée.

INTRODUCTION

L'évolution des postes de pilotage ou de conduite ainsi que l'augmentation de la durée des trajets, que ce soit dans le transport aérien ou ferroviaire, conduisent à une redéfinition du rôle de l'opérateur humain. Cette évolution qui concerne à la fois la nature de la tâche et l'organisation du travail dans le temps est à l'origine d'une série de recherches destinées à évaluer les capacités de l'opérateur humain en termes de vigilance et de performance pendant de longues durées.

Les modifications survenues dans les transports se traduisent dans de nombreux cas par une diminution du niveau d'éveil de l'opérateur. Dans le domaine ferroviaire, des travaux réalisés en laboratoire sur une tâche de conduite simplifiée (1, 2) ont permis d'objectiver cette réduction de la vigilance des conducteurs. Ces résultats se confirment sur le terrain (3, 4).

Parallèlement à ces transformations dans le contenu de la tâche on constate une augmentation de la durée des trajets liée à l'autonomie accrue des moyens de transports, ce qui est très net dans l'aéronautique civile pour les nouveaux avions, notamment le Boeing 747-400, et dans un proche avenir l'Airbus A340. Compte tenu de la législation sur la durée du travail au cours des vols long-courriers ces durées élevées conduisent à des changements radicaux dans la composition des équipages et par voie de conséquence dans la répartition des tâches entre les différents membres de l'équipage. Par ailleurs, les pilotes de vols long-courriers sont soumis aux horaires alternants et aux décalages horaires dans le cas de vols transméridiens. Cette situation peut accroître les baisses de vigilance par les perturbations qu'elle occasionne sur le rythme veille-sommeil (5, 6, 7) avec notamment une diminution de la qualité et de la durée du sommeil.

Les études réalisées au cours de vols long-courriers demeurent primordiales car elles vont permettre d'évaluer la répercussion des contraintes liées à la tâche, notamment la monotonie, les horaires irréguliers et les décalages horaires sur l'efficience des pilotes.

Les baisses de vigilance en laboratoire liées à la monotonie de la tâche ont été montrées par plusieurs auteurs (8, 9, 10, 11). Dans le cas des études réalisées sur le terrain, un certain nombre de problèmes de méthode se posent, notamment dans l'analyse de la tâche et de la détection de baisses de performance. La plupart des études menées sur le terrain utilisent des techniques de monitoring ambulatoire afin de recueillir des paramètres physiologiques. Grâce à ces méthodes, il est possible de mettre en évidence les perturbations du cycle veille-sommeil consécutives à des changements d'horaires. Cependant ces études demeurent généralement limitées aux perturbations des rythmes biologiques et sont peu orientées vers les relations entre la nature de la tâche et les modifications de l'état physiologique. C'est pourquoi deux types d'expérimentations sont en cours sur la conduite ferroviaire et sur des vols long-courriers. Les recherches destinées à objectiver des baisses de vigilance du conducteur dans le domaine ferroviaire ont débuté par des expérimentations de laboratoire utilisant une tâche de conduite simplifiée (1, 2). Ces recherches ont permis de mettre en relation les variations de l'état d'éveil évaluées par l'électro-encéphalogramme avec d'une part des omissions de réponses aux signaux provenant de la voie et d'autre part des perturbations de l'action motrice du conducteur sur le système de sécurité utilisé dans les cabines de train. Ce système fondé sur le principe de "l'homme mort" est constitué de deux pédales et d'une commande manuelle (système VACMA). Le conducteur doit activer ce système et le relâcher périodiquement attestant ainsi de sa présence. L'identification de perturbations motrices offre un moyen de détection de ces hypovigilances lors de la conduite réelle. Une étude de validation d'un système analysant en temps réel l'action du conducteur sur le système de sécurité est actuellement en cours. Si cette méthode de détection est validée, des moyens de réactivation devront être élaborés, notamment par l'utilisation de modifications de la tâche.

Dans le contexte de l'aéronautique, la détection des hypovigilances paraît plus difficile à réaliser dans la mesure où les pilotes ne sont pas astreints à l'utilisation d'un système de sécurité pour attester de leur présence. D'autres moyens devront être imaginés pour permettre d'éviter ou de détecter l'apparition de ces baisses de vigilance. Compte tenu de la présence d'au moins deux pilotes dans la cabine, ces méthodes pourront par exemple s'orienter vers la gestion de cycle activité-repos permettant une récupération optimale de chacun des membres d'équipage.

Le but de la présente recherche est d'évaluer la variabilité du niveau d'éveil des pilotes et d'étudier des possibilités de réactivation ou d'assistance.

METHODE

La méthode et les résultats obtenus sur les premiers vols ont été présentés récemment (12). Cette méthode repose sur le recueil de données physiologiques et sur l'observation simultanée de chaque membre de l'équipage.

Recueil des données physiologiques

Quatre types de mesures sont réalisées :
- l'électro-encéphalogramme (EEG), afin d'étudier, après analyse spectrale, les variations des principaux rythmes : bêta, alpha, thêta et delta,
- l'électro-oculogramme (EOG) dont est extraite la fréquence des clignements oculaires ,
- la fréquence et la variabilité cardiaque,
- l'activité motrice du poignet (actométrie).

L'EEG et l'EOG permettent d'évaluer en continu le niveau d'éveil, et de détecter des périodes de somnolence. Pour l'EEG il a été retenue d'enregistrer une seule dérivation pariéto-occipitale. Cette dérivation nécessite la pose de quatre électrodes collées au collodion : une électrode occipitale, une électrode pariétale, et deux électrodes de terre placées au vertex. Pour le recueil de l'EOG deux électrodes sont fixées : l'une sur une zone électriquement inactive, la mastoïde, l'autre à un centimètre au-dessus de l'oeil. La fréquence cardiaque a été enregistrée au moyen de deux dérivations de type CM5 (creux axillaire droit, creux axillaire gauche) et 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.

Au cours de la rotation le recueil des paramètres est différent au cours du vol et et des repos à l'escale :

- l'actométrie a été recueillie au moyen du système Vitalog et maintenant avec le système Actigraphe qui se révèle plus souple d'emploi, les résultats sont utilisés afin d'identifier les phases de repos des pilotes et de mettre en évidence d'éventuelles privations de sommeil,
- au cours du vol, l'ECG, l'EEG et l'EOG sont recueillis sur le système d'enregistrement magnétique Médilog afin d'étudier les variations de la période cardiaque, le spectre de puissance de l'EEG, le nombre de clignements des yeux.

Observation de la tâche et de l'environnement des pilotes

Parallèlement au recueil de ces mesures physiologiques, une observation chronométrée de la tâche et de l'environnement des pilotes est effectuée. Cette observation est réalisée à partir d'une grille de codage (figure n°1) qui prend en compte divers éléments susceptibles de faire varier l'état de vigilance du pilote.

Les phases et la gestion du vol, l'environnement opérationnel, les communications, la répartition des tâches entre le co-pilote et le commandant de bord, les communications et la météo sont prises en compte pour l'ensemble de l'équipage tout au long de l'expérimentation. La tâche et l'état sont notés pour chaque membre d'équipage.

Les résultats sont analysés :

- en fonction du temps, ce qui permet de détecter les fluctuations les plus marquantes de la vigilance et de la charge de travail,
- en fonction des segments temporels identifiés par l'observation et caractérisés par un code de phase de vol, d'activité des pilotes, etc,...

Ces résultats sont à présent intégrés dans une base de données qui devrait permettre de mieux évaluer les variations physiologiques en fonction du contexte du vol.

Vols effectués

Deux types de rotation ont été effectuées au cours de la phase de mise au point de la méthode :

- des vols transméridiens : Paris-Winnipeg-Paris sur B-747 et Paris-Cayenne-Paris sur DC8
- des vols nord-sud : Paris-Libreville-Paris et Paris-Brazzaville-Paris sur B-747.

Les vol, prévus pour la phase expérimentale, vont concener en plus des rotations précédemment citées :

- des rotations Bruxelles-Libreville-Bruxelles sur Airbus A310 et prochainement Bruxelles-New York-Bruxelles sur Airbus A-320.
- des rotations de longues durées : Paris-Singapour-Paris sur B-747-400.

Au cours de cette phase expérimentale, 50 vols de longues durées seront effectués. En complément de l'observation de la tâche et du recueil des paramètres physiologiques, des questionnaires de sommeil seront utilisés. Ces questionnaires ont été élaborés et seront exploités par le CERMA.

Grille de codage des phases de vol et des tâches de pilotage long-courrier

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	Evènement
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 march.	6 Radio Com.	6 C°.Mainten.	6	6 AP, Visit.<<	6 CL/Panne
7 Approach	7 Final CL	7	7	7 Monit.Carb.	7 C°.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

Etat actuel du codage : - de l'activité des différents membres de l'équipage,
- des conditions du vol et de l'environnement.

Figure n°1

PREMIERS RESULTATS

Evaluation de la vigilance

L'évaluation au cours du temps de la vigilance est fondée sur l'analyse des spectres EEG ainsi que sur la fréquence des clignements oculaires. Du point de vue EEG, la baisse de vigilance se traduit par une augmentation de la puissance dans les rythmes lents (delta, thêta) ou du rythme alpha. Dans le même temps la fréquence des clignements oculaires augmente. La baisse de vigilance peut également être objectivée par une augmentation de la puissance totale du spectre EEG ou par l'étude des rapports de spectre entre les bandes alpha et thêta ou alpha et delta

Pour un vol transméridien qui s'est déroulé entre 14h30 et 23h30 GMT, on constate pour le co-pilote l'apparition d'une période d'hypovigilance 4 heures après le début du vol. Cette hypovigilance se traduit par une augmentation de puissance dans les rythmes EEG lents delta et thêta ainsi que par une augmentation de la fréquence des clignements oculaires (figure n°2). Dans l'ensemble le commandant de bord présente au cours de ce vol une vigilance stable (figure n° 3).

Le vol de retour s'est déroulé après une période de 16 heures de repos à Winnipeg, entre 15h00 et 22h00 GMT. Environ 4h30 après le début du vol, on constate pour le commandant de bord une diminution de la vigilance caractérisée par une augmentation des rythmes delta et alpha et de la fréquence des clignements oculaires (figure n°4). Une seconde période d'hypovigilance apparait à la fin du vol. Chez le copilote, il est également possible de detecter deux périodes de baisse de vigilance, l'une environ 2 heures après le début du vol l'autre un peu plus de 5 heures après le décollage (figure n°5).

Les périodes d'hypovigilance sont donc plus nombreuses lors du vol retour que lors du vol aller. Par ailleurs ces hypovigilances apparaissent plutôt lors des périodes de vol de croisière. Les pilotes présentent un état d'éveil attentif lors des périodes d'approche et d'atterrissage. Le plus grand nombre d'hypovigilances lors du vol de retour s'explique en grande partie par la privation partielle de sommeil lors du repos à l'escale.

La figure n°6 présente un autre exemple de résultats obtenus sur un vol nord-sud pour le co-pilote et le mécanicien. On constate pour ce vol que les périodes d'hypovigilance apparaissent au même moment pour ces deux membres d'équipage au cours du vol de croisière, environ deux heures après le début du vol.

Etude des rythmes veille-sommeil

Ces paramètres permettent d'évaluer les cycles activité-repos au cours de la rotation (figures n°7 et 8). A partir de l'actométrie, il est notamment possible de déterminer avec une bonne précision les heures de lever et de coucher, ainsi que la qualité du sommeil par la fréquence des réveils per-somniques. A l'examen de ces figures, on note pour ce pilote un nombre important de réveils per-somniques caractérisés par une augmentation de l'activité motrice ce qui traduit un sommeil de qualité médiocre.

Observations

Sur le plan de l'observation, il est possible d'évaluer la répartition des tâches, des durées de communication entre le commandant de bord et le co-pilote ainsi que leur état respectif (figures n°9 et 10). L'évolution des communications (figure n°11) constitue également un facteur susceptible d'influencer la vigilance des pilotes. On constate que les baisses de vigilance apparaissent surtout lors de périodes de silence. La diminution des sollicitations survenant lors de ces périodes a un effet sur le niveau de vigilance des pilotes.

Cependant, il est pour l'instant difficile d'associer ces observations avec les variations des paramètres physiologiques tant que l'ensemble de ces paramètres n'est pas intégré dans la base de données.

Néanmoins une première analyse de ces observations a permis de mettre en évidence des facteurs prédominants influençant la vigilance des pilotes :
- la période au cours de laquelle se déroule le vol (de nuit ou de jour),
- les activités antérieures du pilote (repos, décalages horaires, rotations nocturnes),

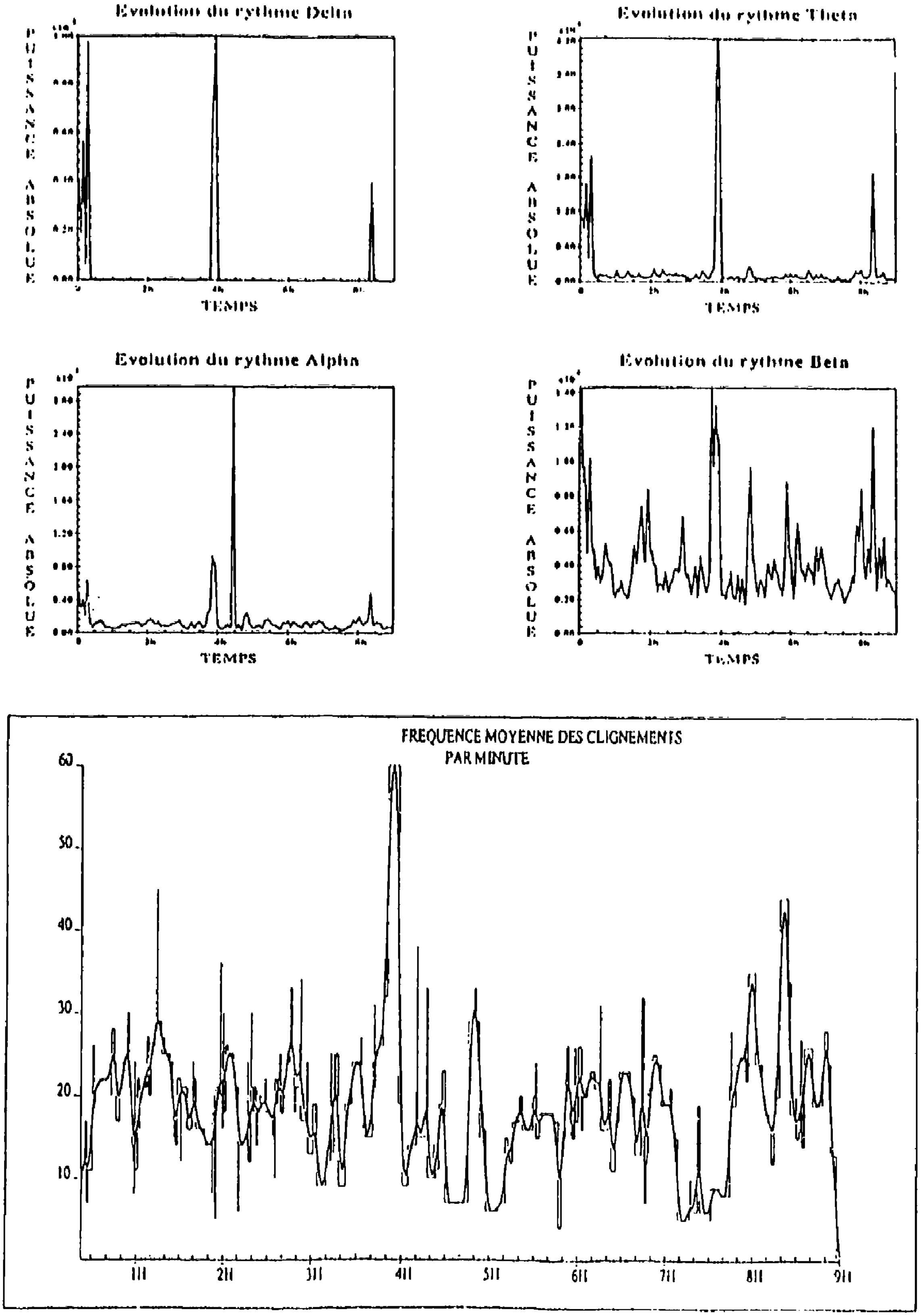


Figure n°2

Evolution des rythmes EEG et de la fréquence des clignements oculaires d'un co-pilote lors d'un vol est-ouest

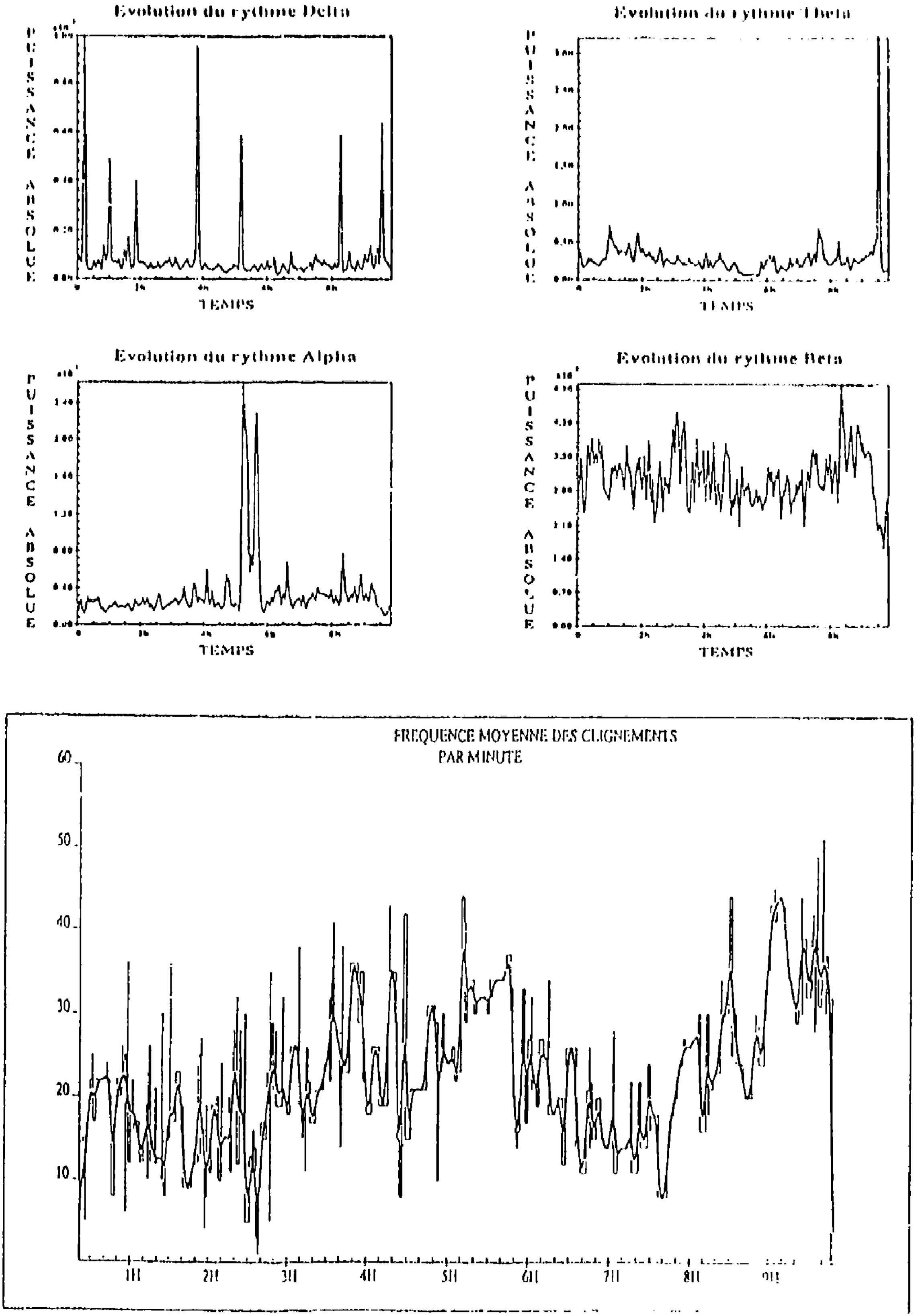


Figure n°3

Evolution des rythmes EEG et de la fréquence des clignements oculaires d'un commandant de bord lors d'un vol est-ouest

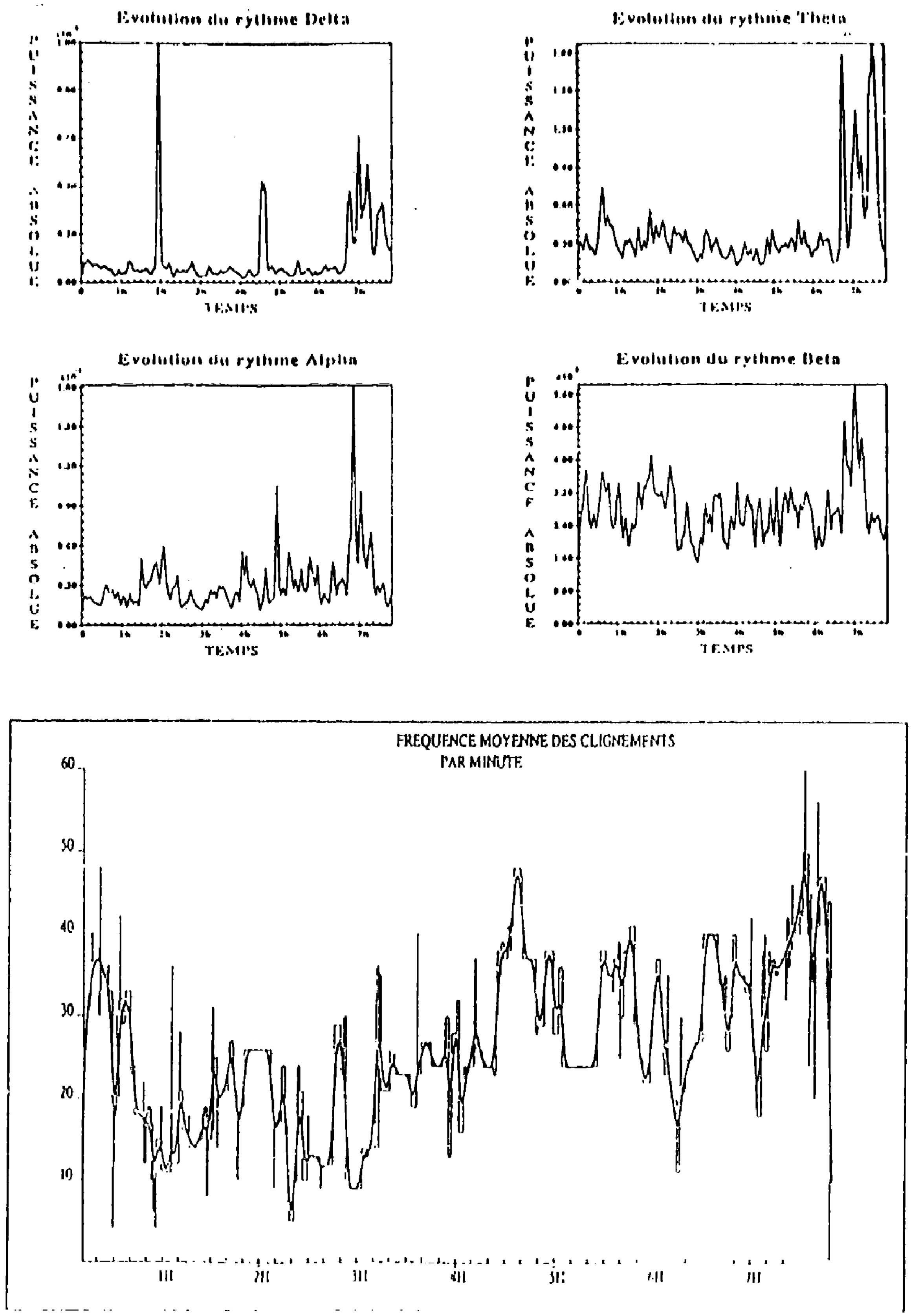


Figure n°4

Evolution des rythmes EEG et de la fréquence des clignements oculaires d'un commandant de bord lors d'un vol ouest est

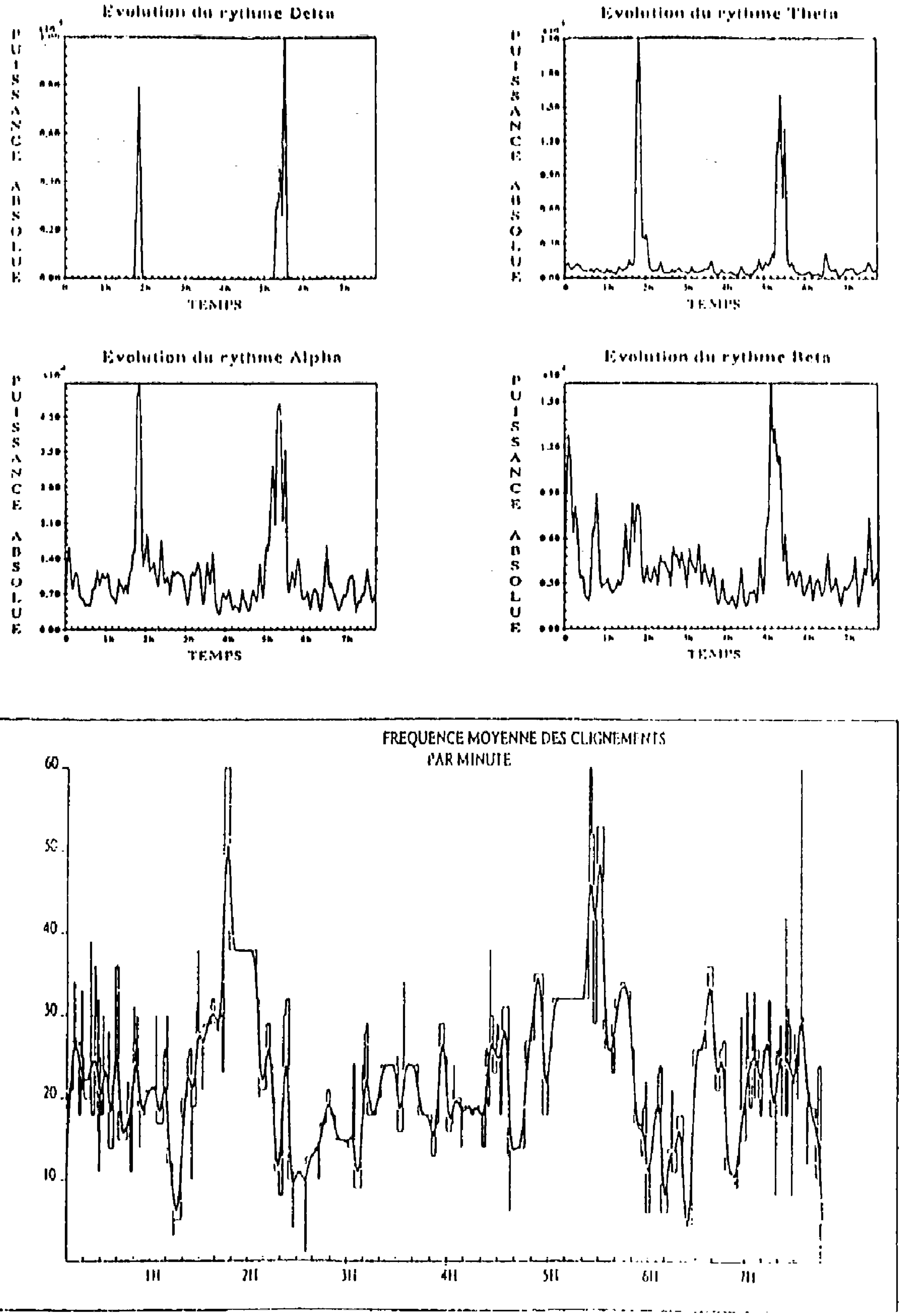


Figure n°5

Evolution des rythmes EEG et de la fréquence des clignements oculaires d'un co-pilote lors d'un vol ouest-est

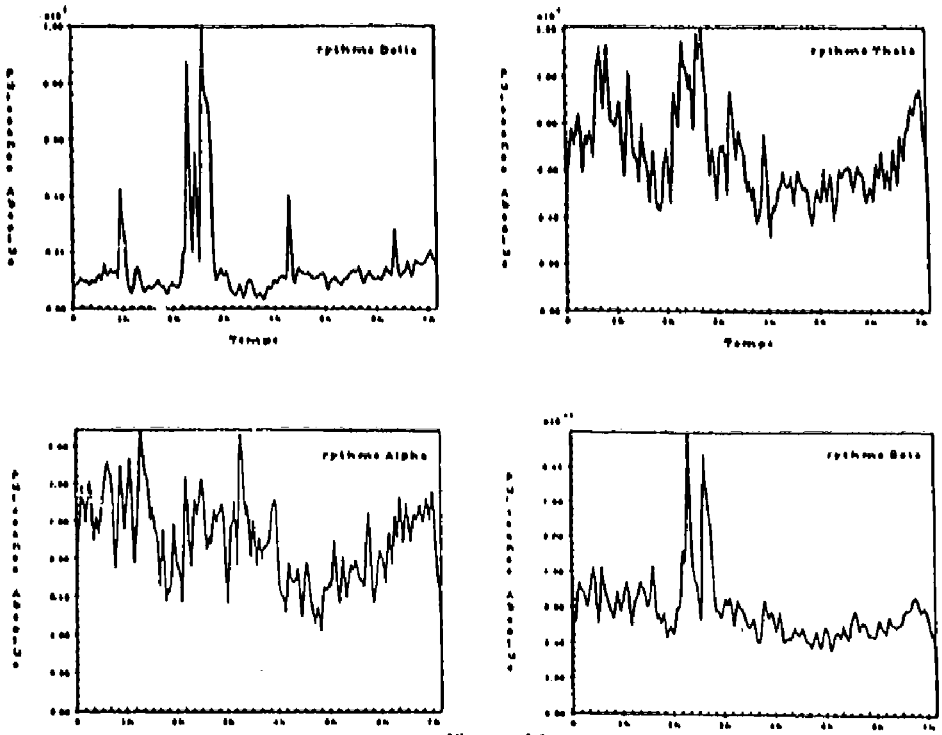
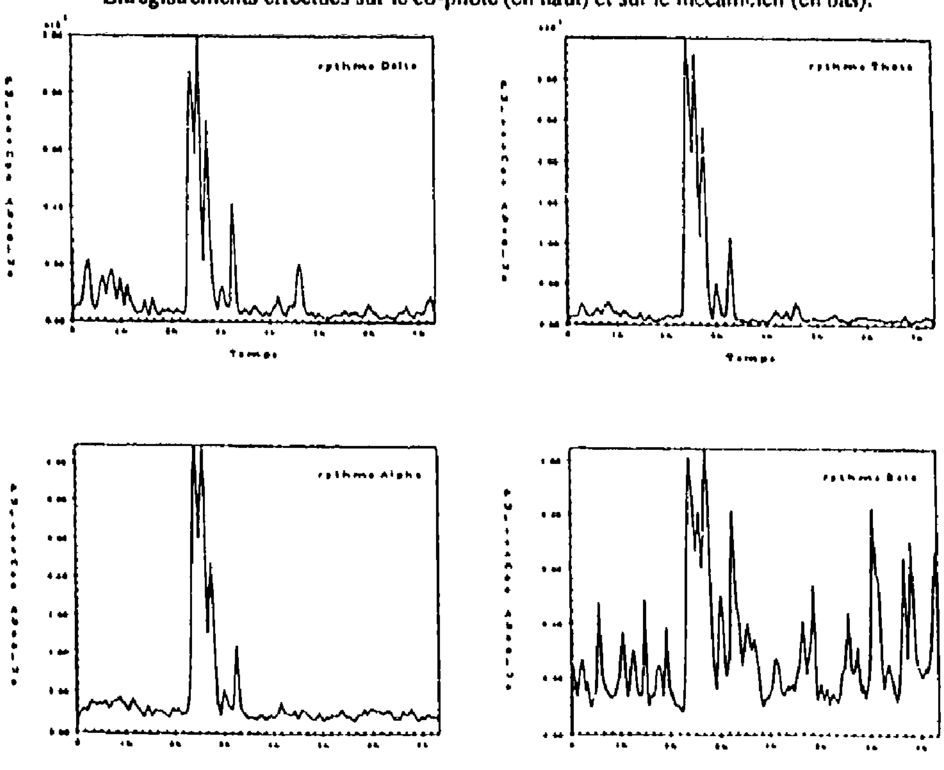


Figure n°6
Exemple d'évolution des différents rythmes EEG pour un vol de jour dans le sens Nord-Sud.
Enregistrements effectués sur le co-pilote (en haut) et sur le mécanicien (en bas).



EVOLUTION DE L'ACTOMETRIE ET DE LA FREQUENCE CARDIAQUE MOYENNE AU COURS D'UN VOL TRANSMERIDIEN

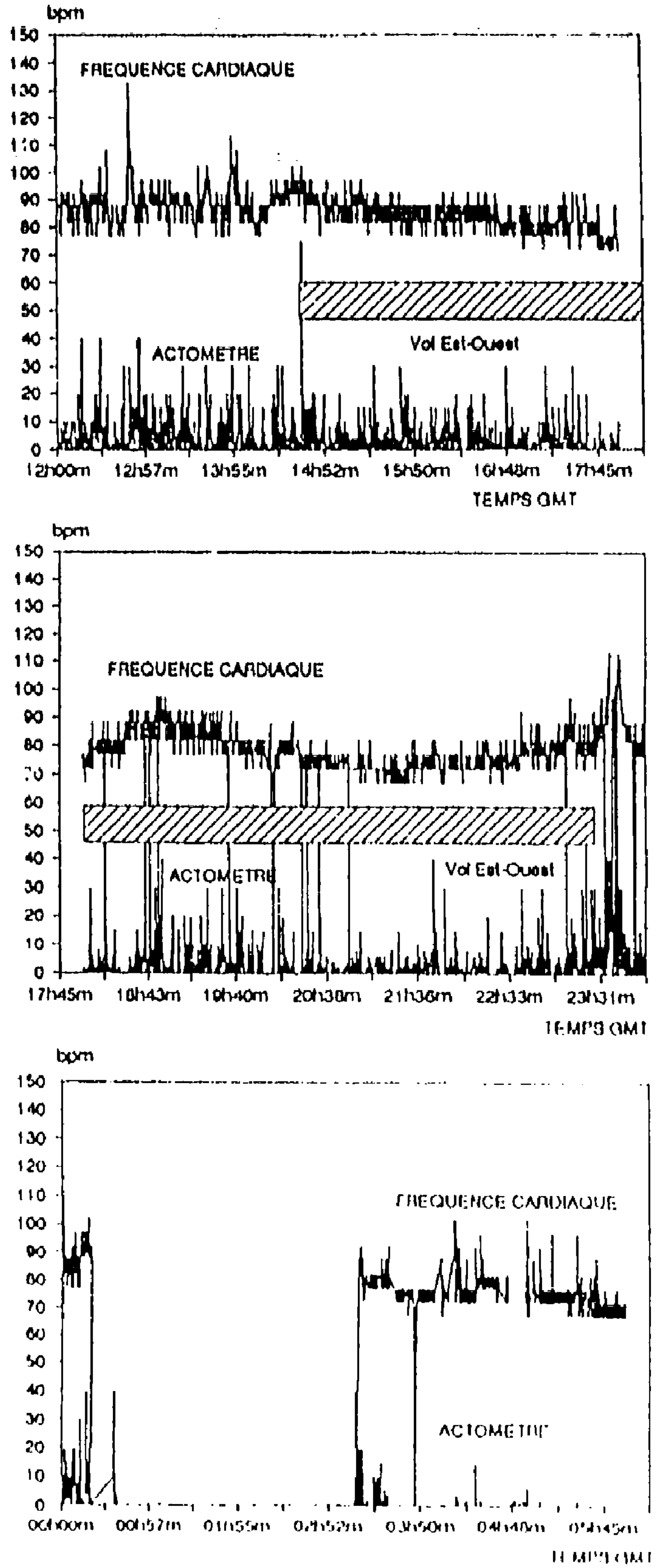


Figure n° 7

EVOLUTION DE L'ACTOMETRIE ET DE LA FREQUENCE CARDIAQUE MOYENNE AU COURS D'UN VOL TRANSMERIDIEN.

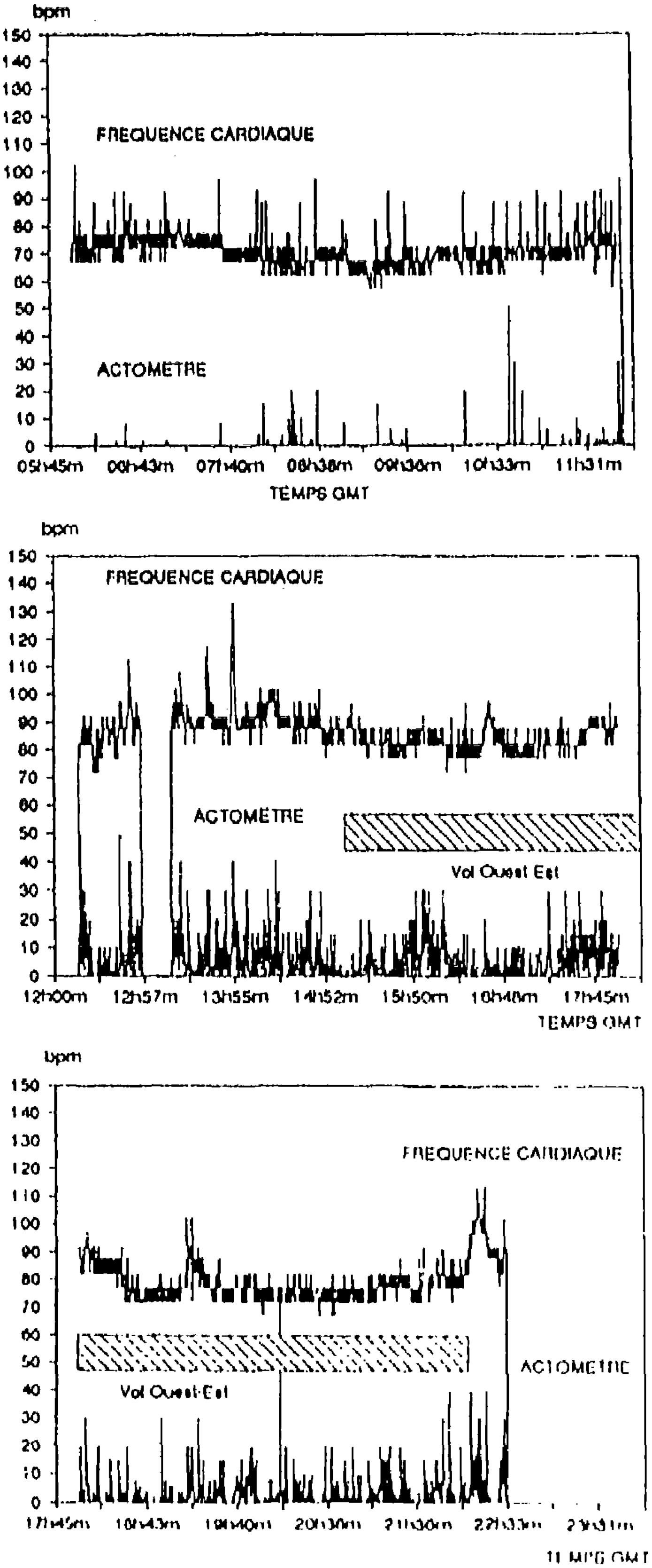
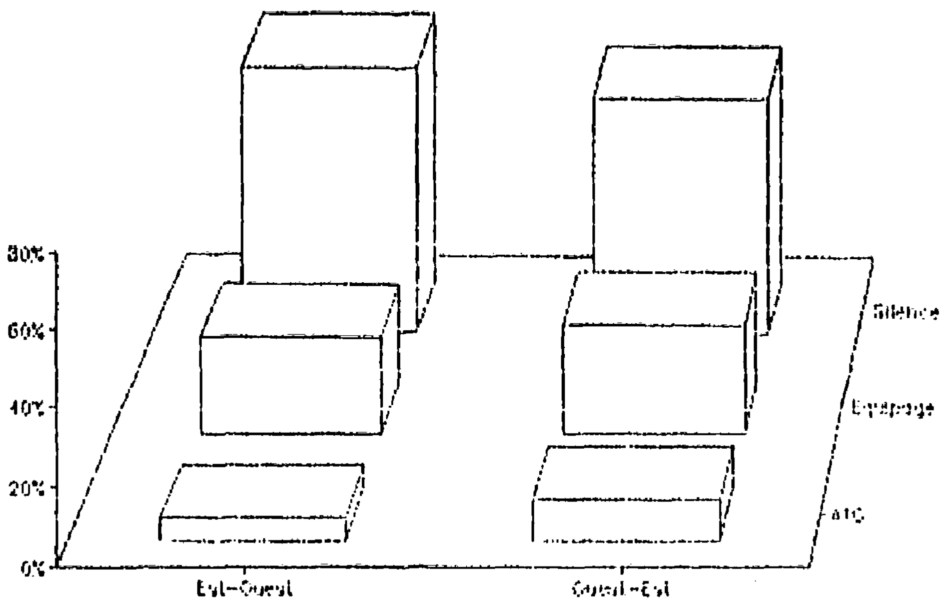


Figure n°8

Répartition des durées de Communication



Répartition des fonctions de pilotage

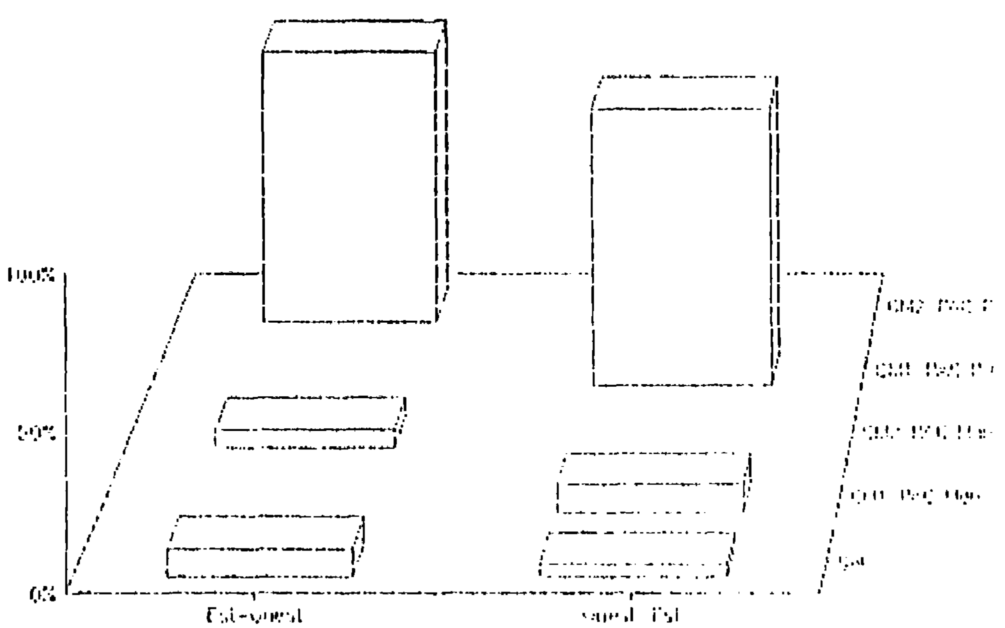
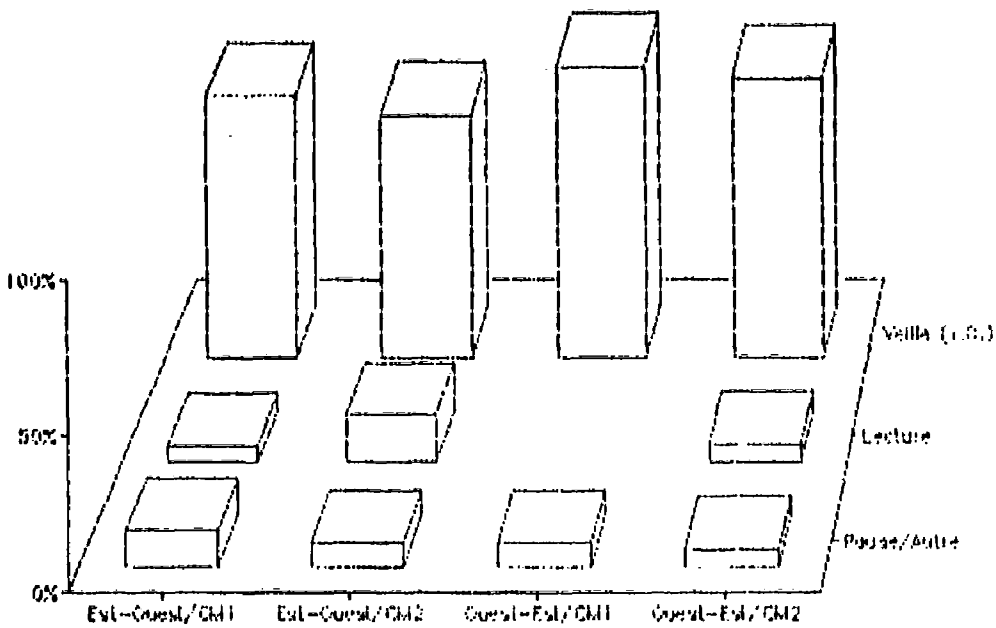


Figure n°9

Répartition des durées d'Etat



Répartition des durées de TACHE

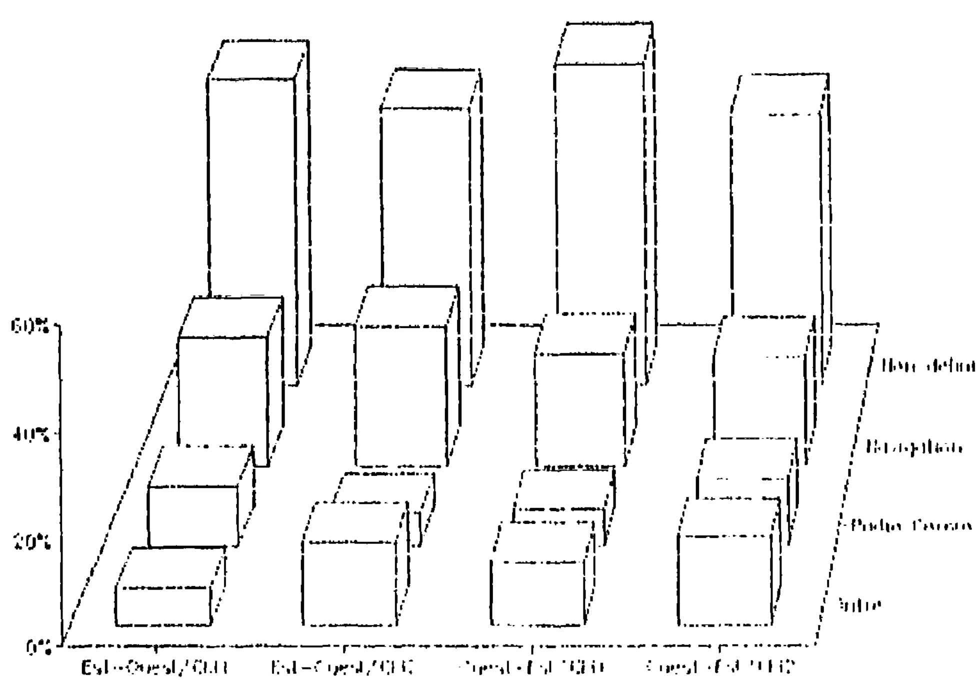


Figure n° 10

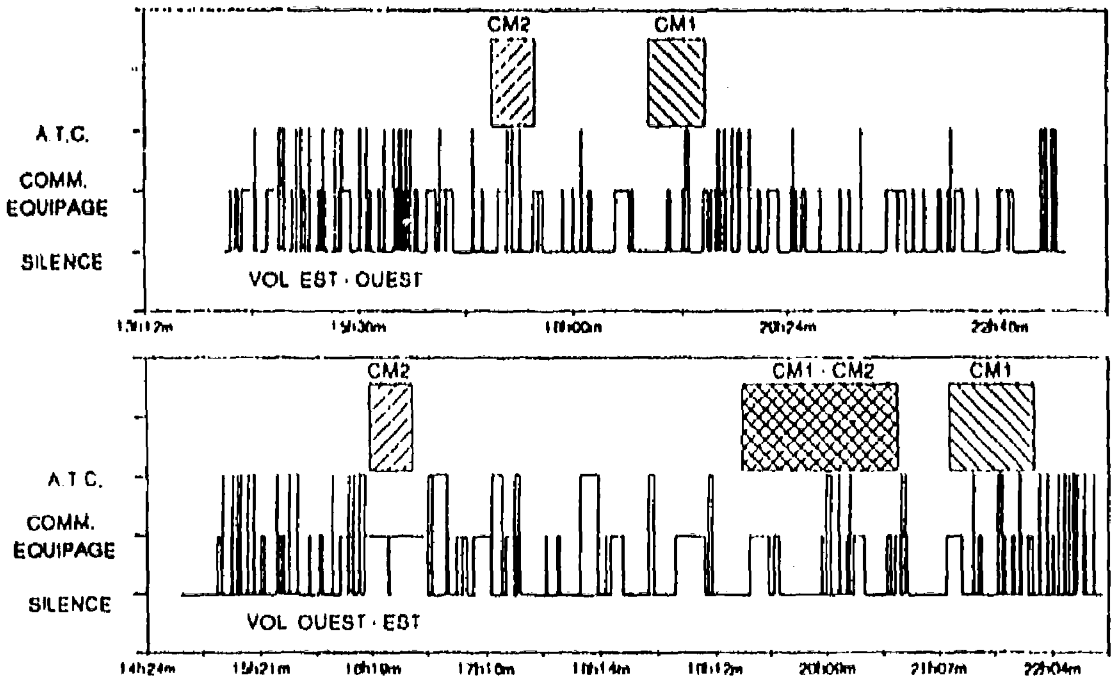


Figure n°11

Evolution des communications au cours de vols transméridiens et phases d'hypovigilance identifiées sur les tracés EEG et EOG.

hypovigilance identifiée pour le commandant de bord

hypovigilance identifiée pour le co-pilote

hypovigilance identifiée pour le commandant de bord et le co-pilote

- la région survolée (zone atlantique à faible trafic aérien, zone terrestre à trafic aérien faible ou important).

Ces premiers résultats devront être confirmés sur les données recueillies lors des prochains vols.

CONCLUSIONS

Compte tenu de l'automatisation de plus en plus importante des postes de pilotage et de l'augmentation de la durée des vols, le problème du maintien du niveau de vigilance des pilotes de vols long-courriers constitue un des problèmes essentiels. L'autre point important réside dans la détection de ces baisses de vigilance au cours du vol.

Dans le but de déterminer les différents facteurs susceptibles d'influencer le niveau de vigilance, une étude a été entreprise dans des conditions réelles de vol.

Le recueil des paramètres physiologiques ainsi que l'observation de l'activité et de l'environnement des pilotes sur des vols long-courriers a permis, lors de cette première étape, de mettre en évidence les points suivants :

- les périodes d'hypovigilance apparaissent en majorité lors du vol de croisière au cours duquel l'activité de l'équipage est faible,
- la diminution des communications et l'apparition de périodes de silence coïncident avec l'apparition de baisses de vigilance,
- sur le vol transméridien étudié les baisses de vigilance sont plus nombreuses lors du vol retour en raison des privations de sommeil et de la fatigue provoquées par la rotation.

La seconde étape de cette recherche se déroule actuellement. Elle porte sur 50 vols long-courriers avec notamment des vols de très longue durée (14 à 16 heures) sur B747-400. 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 cumulatif 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 sommeils de courte durée avec une périodicité et une durée à définir pourraient être proposés dans le but de maintenir l'efficience de chaque membre de l'équipage.

BIBLIOGRAPHIE

(1) - COBLENTZ (A.), IGNAZI (G.), MOLLARD (R.), SAUVIGNON (M.).- Effect of monotony on vigilance and biomechanical behavior In : Vigilance: Methods, Models, and Regulation.-J.P. Leonard ed, 1986, pp. 129-136.

(2) - COBLENTZ (A.), CABON (P.) ; IGNAZI (G.).- Human operator efficiency in monotonous transport operations. Effects on safety. Communication at the 33th Annual Meeting of the Human Factors Society, Denver, 16-20 octobre 1989.

(3) - AKERSTEDT (T.), TORSVALL (L.) ; GILLBERG (M.).- Sleepiness : continuous EEG and EOG measures in the field and laboratory. - In : Proceedings of the CEE Workshop Electroencephalography in Transport Operations/Gundel ed., Cologne : DFVLR, 15-17 sept 1985, pp. 1-13.

(4) - TORSVALL (L.), AKERSTEDT (T.).- Sleepiness on the job : continuously measured EEG changes in train drivers.- Electroencephalography and Clinical Neurophysiology, 66, 1987, pp. 502-511.

(5) - NICHOLSON (A.N.) , STONE (B.M.) , BORLAND (R.G.) , SPENCER (M.B.).- Adaptation to irregularity of rest and activity.- Aviation Space and Environmental Medicine, 55, 1984, pp. 102-112.

(6) - GRAEBER (C.) , DEMENT (W.) , NICHOLSON (A.N.) , SASAKI (M.) , WEGMANN (H.M.).- International Cooperative of Aircrew Layover Sleep : Operational Summary.- Aviation, Space an Environmental Medicine, 57, (12, suppl.), 1986, PP. 3-19.

(7) - NICHOLSON (A.N.) , PASCOE (P.A.) , SPENCER (M.B.) , STONE (B.M.) , GREEN (R.L.).- Nocturnal Sleep and Daytime Alertness of Aircrew after Transmeridian Flights.- Aviation, Space and Environmental Medicine, 57, (12, suppl.), 1986 , pp. 43-52.

(8) - MACKWORTH (N.H.).- Researches on the measurement of human performance, (Medical Research Council, HMSO, London), 1950.

(9) - MACKWORTH, (N.H.).- Some factors affecting vigilance, Advancement in Science, 53, 1957, pp. 389-393.

(10) - JERISON (H.J.) ; PICKETT (R.M.).- Vigilance : The importance of the elicited observing rate, Science, 143, 1964, pp. 970-971.

(11) - SAITO (M.).- A study of bottle inspection speed-determination of appropriate work speed by means of electronystagmoraphy, Journal of Science of Labor, 48, 1972, pp.- 395-400.

(12) - COBLENTZ (A.) ; FOUILLOT (J.P.) ; MOLLARD (R.) ; CABON (Ph.).- Baisse de la vigilance et conscience de la situation des pilotes au cours de vols long-courriers. In : Situational Awareness in Aerospace Operations, Copenhegue, 2-6 Octobre 1989.- AGARD.- pp. 18/1-18/9.

COMPUTER AIDED PHYSIOLOGICAL ASSESSMENT OF THE FUNCTIONAL STATE OF PILOTS DURING SIMULATED FLIGHT

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ABSTRACT

Multichannel (polygraphic) analysis of cardiovascular and neurophysiological parameters provides very sensitive indicators of the functional state of subjects such as pilots during real or simulated flight missions which thus can be objectively assessed (refs. 7, 8, 9).

In 6 subjects (officer pilots of the Luftwaffe and of the Canadian Air Force) flying a fighter jet simulator with ALPHA JET dynamic characteristics without self motion, systolic and diastolic blood pressure, four channel electroencephalogram (EEG), the electrooculogram (EOG) and the electrocardiogram (ECG) were continuously recorded during a rest - activity - rest sequence of 60 min duration. The activities consisted of tracking another plane flying ahead of the piloted plane with four different degrees of difficulty.

The analysis of the data, especially those of the EEG by Fast Fourier Transformation (FFT), revealed task dependent, and in case of the EEG, topographically different cortical activities depending upon whether sensory and/or motor systems were involved.

The physiological measures thus obtained can serve as an objective criterion to assess the functional state of pilots and may serve - especially if only an interval of the order of seconds between data acquisition and data analysis is achieved - as part of an automatic safety network not only in the event of sudden loss of consciousness but also in cases of lowered pilot vigilance due to fatigue.

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INTRODUCTION

The investigation of EEG changes due to pilot stresses in flight or flight-related environment dates back to the pioneering studies of SEM-JACOBSEN (1959), ADEY (1963), SIMONS and BURCH (1963) and others.

We presented in 1978 results of computer aided electroencephalographic assessments of functional brain states investigated in the laboratory (ref. 6) and some years later preliminary results of inflight EEG studies on pilots during different flight maneuvers (ref. 7, 9). Quite recently we investigated a new antihistaminic drug in a flight simulator environment (ref. 8) in order to evaluate the reported absence of unwanted side effects such as sedation endangering the manual control of aircraft.

In this paper investigations on military pilots performing tracking tasks with different degrees of difficulty in a fighter plane simulator are presented. This study was planned in order to establish sets of neurophysiologic baseline data for future inflight studies under various conditions which negatively influence vigilance and control capabilities of pilots.

METHODS

a) Subjects

Six military pilots with a flying experience of at least 1200 flight hours participated in this study.

The subjects were recruited from a Luftwaffe wing operating Phantom reconnaissance aircraft. They were informed about the purpose of the investigation. Free consent was obtained.

No formal neurological examination of the subjects was performed, but all were well known to their flight physician and in bona fide good health according to the regular medical examinations required of military pilots.

b) Design of the study

After briefing and familiarization with the Alpha jet flight simulator each subject made two simulator flights (Series A and B). The second flight was one day after the first flight and at approximately at the same hour of the day in order to exclude possible circadian biological rhythm effects.

The EKG, EOG, systolic and diastolic blood pressure was recorded.

Four channels of longitudinal bipolar EEG were recorded according the 10 - 20 system: F3 - C3 (#1), P3 - O1 (#2), F4 - C4 (#3), and P4 - O2 (#4). Filter setting for upper frequency 30 Hz, time constant for lower frequency 0.1 s.

The EEG, EKG and EOG signals were stored on an FM instrumental cassette data recorder TEAC HR-30E.

Signal deterioration or loss due to external noise (a flight simulator environment is no Faraday cage), movement or myographic artifac s , and technical failures of the battery operated signal amplifiers required visual inspection and discarding of all unusable data during playback of the original data after the experimental series. This resulted in a signal loss of approx. 20 % of the original data.

The EEG was analyzed off-line in 4-second segments using an FFT algorythm. Computed were amplitude spectra. Numerical values of absolute uncalibrated amplitude in the frequency range from 0.5 to 32 Hz and relative (%) values of the frequency bands delta (0.50 to 3.75 Hz), theta (4.00 to 7.75 Hz), alpha (8.00 to 13.75 Hz), beta 1 (14.00 to 22.75 Hz), beta 2 (23.00 to 32.00 Hz), and the dimensionless ratio theta/alpha were computed from the spectra.

c) Statistics

Parametric and nonparametric statistics of the EEG variables was performed.

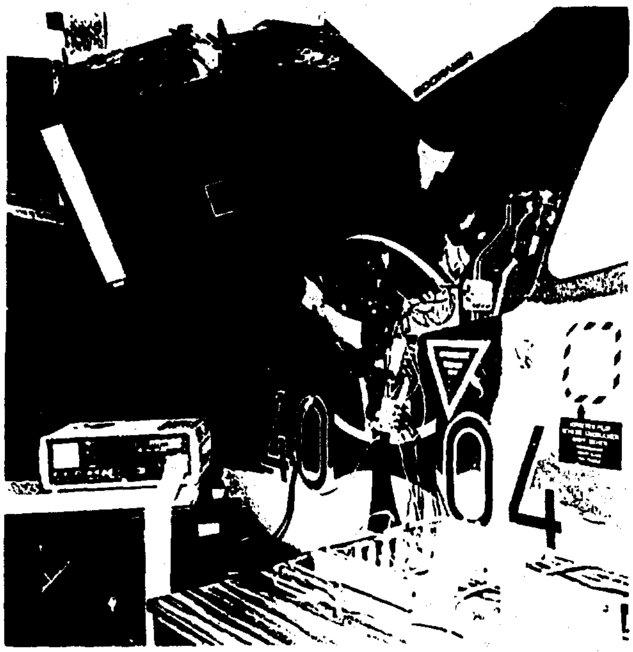


Fig. 1 View of the experimental setup. Alpha-Jet fighter simulator with subject having EEG electrodes and arm cuff attached is shown. In the foreground parts of the biomedical equipment is seen.

Subjects Code	Rank.	1st Flight (Series A)	2nd Flight (Series B)
P1	Hptm.	23.02.1988, 09:07 (40')	24.02.1988, 08:51 (39')
P2	Hptm.	23.02.1988, 10:55 (38')	24.02.1988, 10:12 (40')
P3	Olt.	23.02.1988, 12:42 (45')	24.02.1988, 11:35 (36')
P4	Hptm.	29.03.1988, 09:30 (40')	30.03.1988, 09:40 (37')
P5	Capt.	29.03.1988, 10:46 (37')	30.03.1988, 10:47 (33')
P6	Olt.	29.03.1988, 11:59 (39')	30.03.1988, 11:59 (33')
	avg. flight duration	40'+/- 3'	36'+/- 3'

Tab. 1 Schedule of the experiments. All subjects by rank and initial, dates and hours (in brackets duration of experiment) of first and second simulator flight are listed.

RESULTS

The results of the cardiovascular and oculomotor investigations will be presented in a separate report which is in preparation. The most interesting results have been obtained from the electroencephalographic investigations which are reported here.

An example of the FFT EEG data is given in Fig. 2.

As seen in Fig. 2 which displays the amplitude spectra of subject P1 (second flight on 24 February 1988) the physiologically dominant activity during rest in the alpha band is markedly reduced during the four simulated flight conditions. This effect is due to the cortical activation which results in a desynchronization of the EEG activities.

In addition, during the simulated flight conditions spectral components appear in the delta band (mainly due to movement artifacts) and in the beta bands (mainly due to myographic artifacts).

Since the adjacent frequency bands to the alpha band, namely theta and beta 1 are relatively invariant to movement and myographic artifacts plots of the data of all subjects, all channels, and all conditions are given in Fig. 3 (Plot %alpha vs. %theta) and in Fig. 4 (Plot %alpha vs. %beta 1) respectively.

These plots display characteristic distributions of the data in which e.g. individual subjects can be localized. Individual characteristic EEG patterns are well known to EEG analysts. In the way they are plotted here in a two parameter plane they can be easily recognized.

A two-dimensional plot of the averages of the different conditions investigated is shown in Fig. 5. Clearly, the activity cluster of the four simulation tasks is separated from the prior rest and subsequent rest conditions. A blow-up of the distribution of only the four simulation tasks is plotted in Fig. 6. As can be seen, simulation tasks 2 and 3 are much alike according their %alpha vs %theta parameters, task 1 is located between the simulation task 4 and the simulations tasks doublet 2 and 3.

The arrangement of the different tasks in the primary orthogonal %alpha vs %theta plane as depicted in the primary grid (....) is also shown in a second and rotated orthogonal grid (-.-.) which takes into account the negative intercorrelation of the %theta with the %alpha values.

This arrangement of the four simulation tasks in the %alpha vs. %theta plane as depicted in Figs. 5 and 6 were, however, computed from all the four EEG channels combined.

Fig. 7 presents each of the four EEG channels separately. Here the differences between the the simulation tasks 1, 2, 3 and 4 are computed for the %alpha band of the EEG.

The two occipital EEG channels show a clear increase in desynchronization due to increasing occipital activation by the simulation tasks 2, 3, and 4. The motor channels show quite a different pattern. The largest amount of desynchronization is seen here already in the first simulation task. During simulation tasks 2 and 3 there is less desynchronization. This can be physiologically explained as a motor adaptation of the subjects to the simulation tasks performed with less cortical motor activation in the sequence 1 - 2 - 3. Simulation task 4 required again a motor cortex activation comparable with simulation task 2 irrespective of this adaptation process.

Interestingly, these effects were more pronounced in channel #1 than in channel #3. Since the control stick was moved by the right hands of the pilots these effects are expected to be more pronounced in the contralateral left cortical hemisphere due to afferent and efferent crossing of nerve fibers.

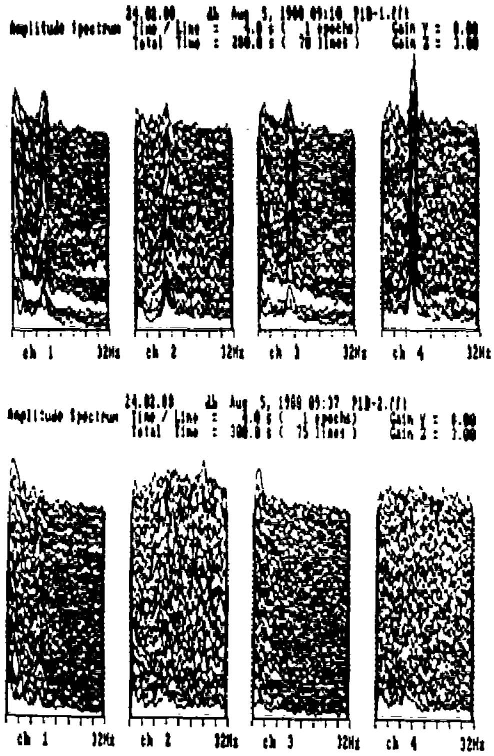
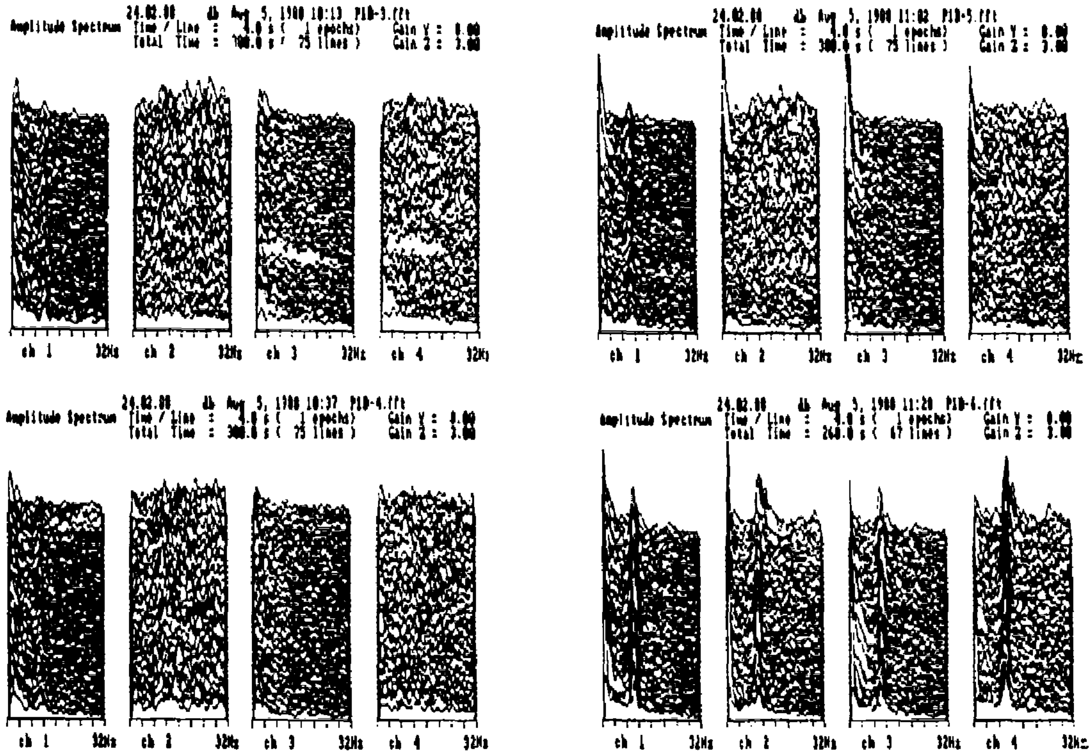


Fig. 2

Examples of FFT EEG spectra
Subject P18 (B=second flight)
-1 Prior rest
-2 Simulation task 1
-3 Simulation task 2
-4 Simulation task 3
-5 Simulation task 4
-6 Subsequent rest
ch(annels) 1 to 4



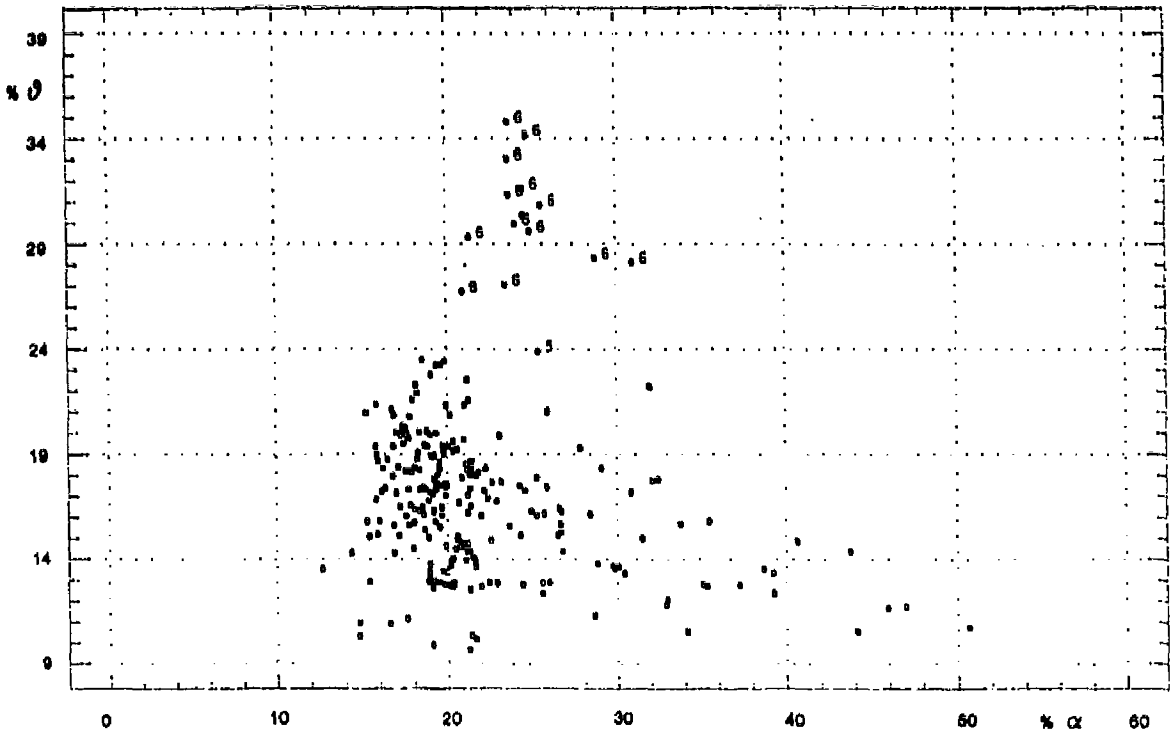


Fig. 3 Distribution of the data of all subjects, all conditions and all channels in the %ALPHA vs %THETA plane. Subject P6 is marked.

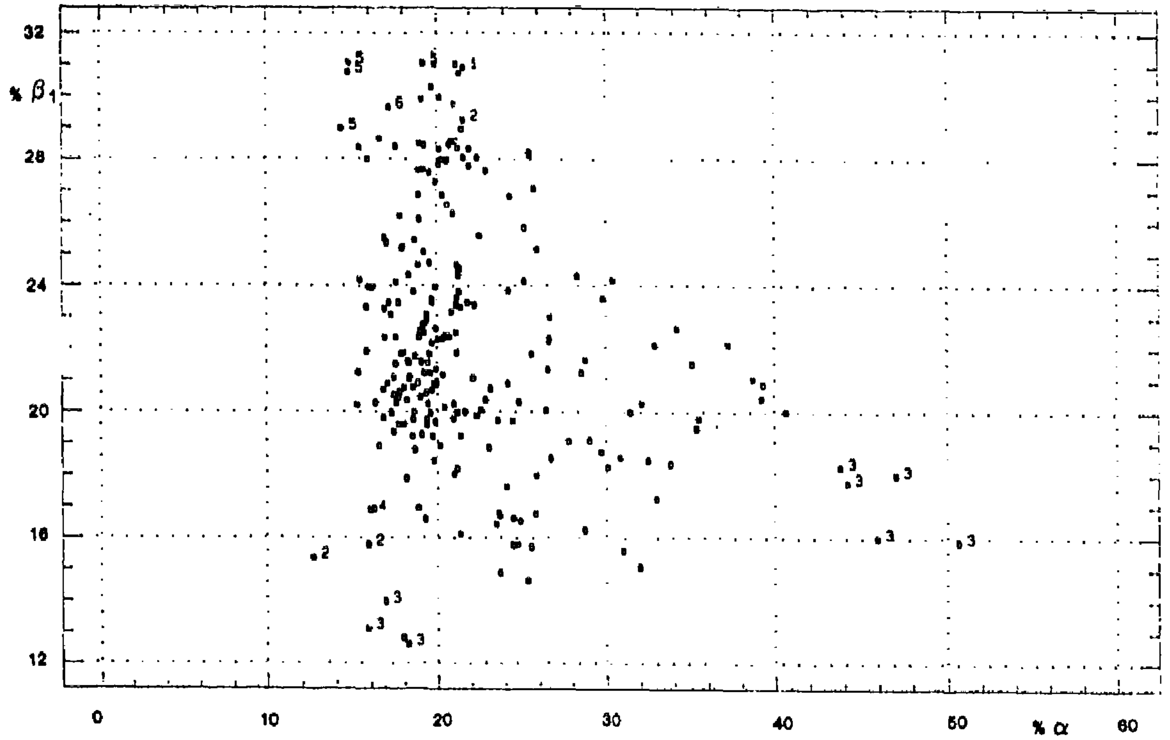


Fig. 4 Distribution of the data of all subjects, all conditions and all channels in the %ALPHA vs %BETA 1 plane. Some subjects are marked.

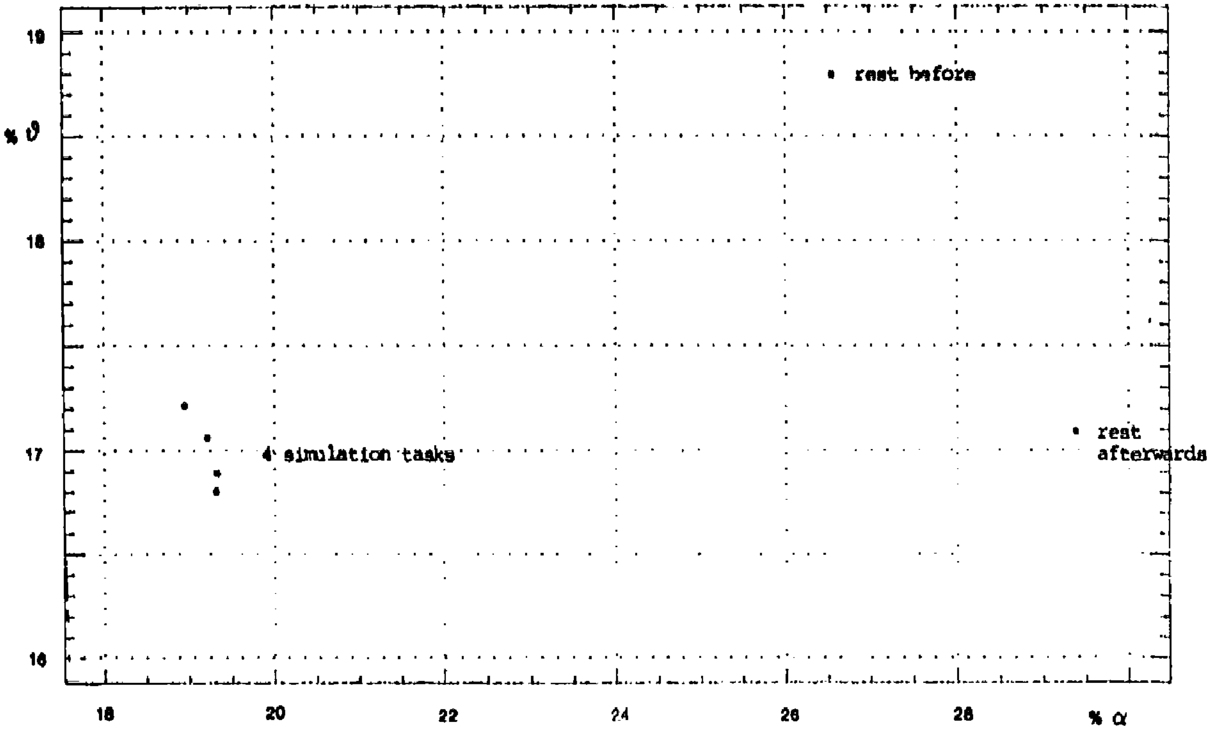


Fig. 5 Distribution of the averages of all subjects and all channels combined in the %ALPHA vs %THETA plane. All 6 conditions are shown.

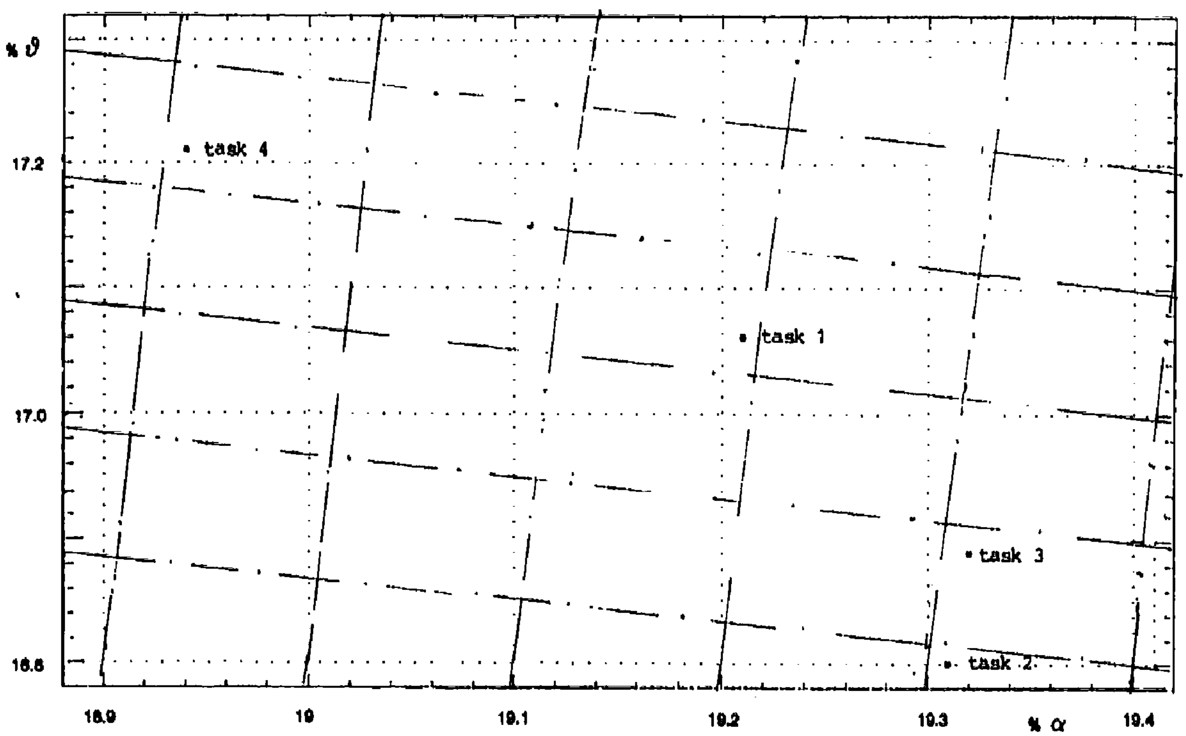


Fig. 6 Distribution of the averages of all subjects and all channels combined in the %ALPHA vs %THETA plane. Only task conditions are shown. Explanation of two grids see text.

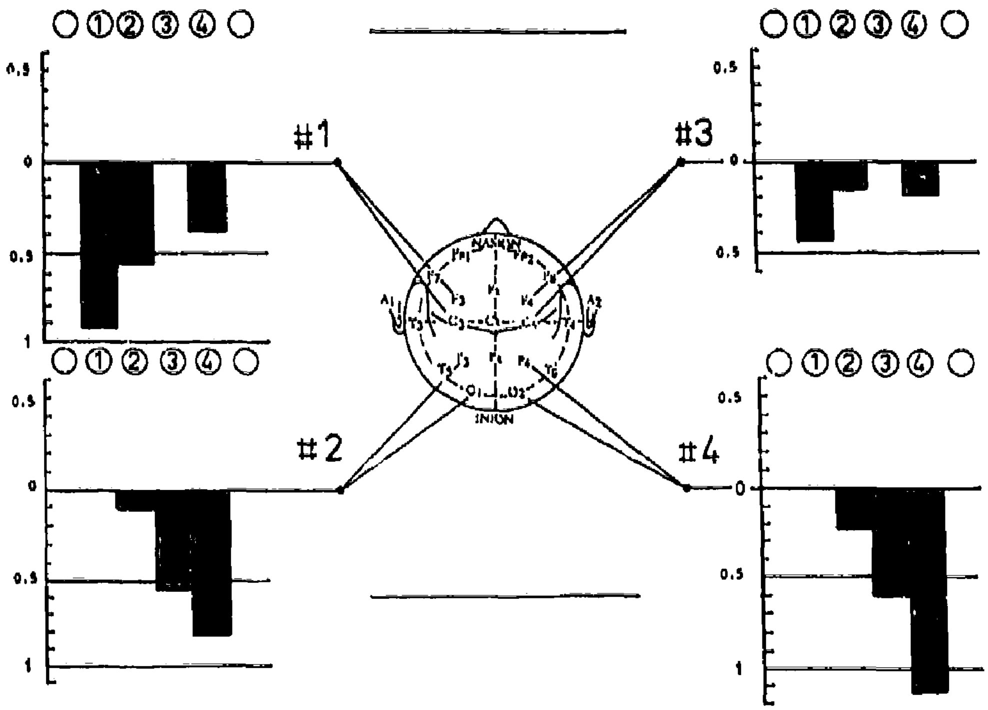


Fig. 7 Cortical regional average changes of all subjects in the %ALPHA band. Only task conditions 1, 2, 3, and 4 are shown.

DISCUSSION

As mentioned in the introductory chapter the usefulness and potentiality of electroencephalographic methods in aviation and space medicine have been demonstrated by SEM-JACOBSEN (1959), ADEY (1963), SIMONS and BURCH (1963) (refs. 1, 11, 12).
Our group has been investigating by computer-aided EEG analyses functional brain states under various conditions (ref. 6) which by improving our methods have been extended to investigations under inflight (refs. 7, 9, 10) and simulated flight (ref. 8) conditions.
The results reported in this paper extend our earlier investigations of task dependent activation patterns mainly of the occipital cortex (ref. 9) to the somesthetic and motor cortex and implement our earlier observations (ref. 7) during manual control.

Attempts to investigate cortical potential changes associated with hand movements were first reported in detail by Bates (1951).
Quite recently Cooper et al (1989) studied during a 18 sec smooth pursuit tracking task slow waves in the EEG which were found to be correlated with target velocity and having their maximum at the vertex.
In our study the pursuit tracking tasks were more complicated ones and close to flight reality. The EEG parameters indicated also motor adaptation processes of the pilots to the simulated tasks. This effect was limited to the sensorimotor cortex contralateral to the stick's controlling right hand.

REFERENCES

1. ADEY W R
   EEG in simulated stresses of space flight including vibration and centrifuging
   Electroenceph clin Neurophysiol 1963; 15: 165

2. BATES J A V
   Electrical activity of the cortex accompanying movement
   J Physiol (Lond) 1951: 113: 240 - 257

3. COOPER R, McCALLUM W C, CORNTHWAITE S P
   Slow potential changes related to the velocity of target movement in a tracking task
   Electroenceph clin Neurophysiol 1989; 72: 232 - 239

4. DELMER C, FODIL D, DREANO E
   A problem for interpretation in EEG topographic mapping.
   Electroenceph clin Neurophysiol 1989; 72: 36P

5. FISCH B J, HAUSER W A, KELLER D L, PEDLEY D A
   EEG topography: a comparison of bipolar and linked ear reference recordings
   Electroenceph clin Neurophysiol 1989: 72: 13P

6. OFFENLOCH K
   Neurophysiological assessment of functional states of the brain
   AGARD Conference Proceedings 1978; 216: A 10

7. OFFENLOCH K
   Vigilanz und Motorik
   Z EEG-EMG 1984; 15: 203 - 205

8. OFFENLOCH K, ZAHNER G
   Behavioral ratings, cardiovascular, and quantitative EEG parameters during simulated instrument flight under the effect of terfenadine
   (In preparation)

9. OFFENLOCH K, ZAHNER G, NICKEL B, BRUNNER D
   Zielverhalten und Auge-Hand Koordination. In: BENTE D, COPER H, KANOWSKI S (eds) Hirnorganische Psychosyndrome im Alter II
   Berlin-Heidelberg-New York-Tokyo; Springer 1985, pp 105 - 112

10. OFFENLOCH K, ZAHNER G, DIETLEIN G, FRANZ I
    Vergleichende Inflight-Untersuchung eines Scopolamin-haltigen Membranpflasters versus Dimenhydrinat unter definierten Beschleunigungsreizen
    Arzneim-Forsch/Drug Res 1986; 36 (II) 9: 1401 - 1406

11. SEM-JACOBSEN C W
    Electroencephalographic study of pilot stresses in flight
    Aerospace Medicine 1959; 30: 797 - 801

12. SIMONS D G, BURCH N R
    Telemetry and automatic analysis of the electroencephalogram under simulated flight conditions
    Electroenceph clin Neurophysiol 1963; 15: 165 - 166

DEVELOPMENT OF A TEST-BED FOR REAL-TIME MONITORING OF PILOT MENTAL STATUS

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SUMMARY

The real-time determination of pilot mental and physical status is a critical feature of the workload monitoring and "Mindware" subsystems that have been envisioned for future jet aircraft. Recent laboratory and simulator studies, using retrospective data analyses, have suggested the value of various behavioral and physiological indices for reflecting task performance. The purpose of the present work was to develop software algorithms to derive some of these measures of interest in real-time and to develop a test-bed in which to explore the efficacy of these measures for inferring operationally relevant changes in pilot status. Such a test-bed should prove useful in supporting future studies of dynamic decision-aiding and task partitioning between the pilot and on-board automation.

The present project demonstrated the feasibility and usefulness of this approach. Data processing algorithms were developed for characterizing and integrating physiological indices based on heart-rate and heart-rate variability (vagal tone), eye blinks, and single-trial, scalp-recorded event-related potentials. These physiological measures were obtained concurrently with behavioral measures as subjects performed a PC-based, aviation simulation task (Window/PANES). The data processing algorithms were implemented in a distributed processing configuration, using multiple personal computers, with the derived measures being integrated by a "Decision-Maker" processor. This multi-processor test-bed was demonstrated to work in near real-time (with lags of five to ten seconds), and attained encouraging levels of accuracy in characterizing the physiological phenomena of interest. Also encouraging were preliminary efforts to define decision rules, customized for individual subjects, that reflected a sensitivity of the measures derived in "real-time" to manipulations of task difficulty.

INTRODUCTION

The real-time determination of pilot mental and physical status is a critical feature of the workload monitoring and "Mindware" subsystems that have been envisioned for future fighter aircraft, as well as the "Safety Network" addressed by the present conference. This requirement is based on the fact that the human pilot has certain mental capabilities for pattern recognition and decision-making that are not yet achievable by artificial intelligence. Therefore, given sufficient cognitive capacity on the part of the pilot, many "higher level" functions in the control of complex systems are best left to the human operator. However, on-board automation capabilities have advanced to the point that, if the human operator is debilitated either physically or mentally, due to cognitive overload, fatigue, illness, or injury, it is preferable for certain functions to be taken over by automated subsystems. The picture that emerges for future man-machine interfaces in many systems is, therefore, one of tasks being dynamically traded off between man and machine, depending on the moment-to-moment demands of the task environment and the functionality of the human operator. In order to realize such dynamic control scenarios, on-board systems must be provided with information about the mental status of the human operator in real-time.

Recent laboratory and simulator studies, using retrospective data analyses, have suggested the value of various behavioral and physiological indices for reflecting task performance. Behavioral measures typically involve some aspect of response speed and accuracy, and may be logged separately for multiple tasks being performed concurrently. The physiological indices that have proven most sensitive to cognitive task manipulations include heart rate and heart rate variability derived from the electrocardiogram (ECG) (e.g., see 1), eye blink frequency and duration derived from the electrooculogram (EOG) (e.g., see 2), and scalp-recorded event-related potential (ERP) amplitude and latency derived from the electroencephalogram (EEG) (e.g., see 3). These indices can be obtained unobtrusively, without burdening the pilot with contrived secondary tasks or subjective ratings (4), and progress is being made in the development of hardware that will allow these indices to be faithfully transduced and recorded in-flight (see 5). However, there has not been a great deal of work on software algorithms that would allow these measures of interest to be derived in real-time (or near real-time), nor in exploring the implications of attempting to use such derived measures for dynamic decision-aiding or task partitioning between pilot and on-board automation.

The goal of the work reported here was to demonstrate the feasibility of monitoring, in real-time, the mental status of the operator in a multi-task man-machine control system, using a combination of behavioral and physiological measures. In order to do this, a test-bed was developed within which multiple behavioral and physiological measures can be concurrently obtained and processed in real-time, as an experimental subject performs a simulated aviation task. The scope of the project under which this work was conducted did not allow a major system development effort. Thus the present test-bed was configured using existing hardware -- a number of IBM-compatible personal computers (PCs) with commercially available plug-in boards to accomplish analog to digital (A-to-D) conversion, digital input/output (I/O), and serial communications. The focus was on the development of real-time algorithms for processing the physiological indices of interest in order to obtain useful derived measures in near real-time, and on the development of software to integrate these measures and allow the system supervisor (i.e., the experimenter) to interactively apply decision rules to these derived measures. The specific research objectives were as follows:

o Develop real-time versions of several existing data analysis algorithms (for quantifying eye blinks from EOG and cognitive event-related potentials from EEG).

- Adapt Window/PANES aviation simulation for the present test-bed.
- Develop "decision-making" software to poll and integrate the various behavioral and physiological indices being computed in real-time.
- Construct a working test-bed configuration using existing hardware and system software.
- Collect preliminary data to validate the usefulness of this test-bed and to derive "first-cut" decision rules for delineating operator "mental status".
- Formulate plans for future uses and development of this technology.

Initial validation of this test-bed involved an examination of the sensitivity of the real-time algorithms to manipulations of the physiological signals, both simulated and actual. Then preliminary investigations were conducted to demonstrate the usefulness of the test-bed approach. Appropriate parameters for the pattern recognition algorithms (ECG, ERPs, and "decision rules") were determined by conventional analyses of the data collected as a subject performed the aviation task during a "training set" session. These parameters were then applied in real-time to the data collected from the same individual during a subsequent "test set" session. The objective during the "test sets" was to determine how accurately known task manipulations of cognitive workload could be inferred from combinations of the derived real-time measures.

The focus of the present report will be to provide a description of the test-bed configuration and a qualitative summary of the testing completed to-date. The intent is to demonstrate the feasibility of this approach and its potential usefulness. In that spirit, some potential future directions of this research are also suggested.

OVERVIEW OF THE TEST-BED

Figure 1 provides a schematic of the multi-processor test-bed that was configured for the present development effort. A PC-based, low-fidelity aviation simulation was used as the task environment. The tasks involved here included psychomotor tracking, choice reaction time to occasional transient stimuli, and monitoring the level of gauges which indicated system status. Task difficulty and, by inference, mental workload, was manipulated systematically, as subjects performed in this multiple-task environment. The aviation simulation yielded behavioral measures of primary task performance (root-mean squared tracking error) and secondary task performance (choice reaction-time and accuracy of responses to the transient stimuli and to the occurrence of abnormal conditions indicated by the gauges).

Physiological measures included heart rate and vagal tone derived from the ECG, the frequency of occurrence, duration, and timing of eye blinks derived from the EOG, and the amplitude and latency of several endogenous components of the scalp-recorded ERPs derived from the EEG. A distributed processing approach was implemented whereby a separate PC processed each type of physiological signal. The resulting derived measures were conveyed, by serial communications, from these individual processors to a "Decision-Maker" processor. The Decision-Maker polled and stored these incoming data and implemented some simple pattern recognition algorithms to allow the triggering of "cautions and warnings" when certain measures exceeded pre-selected set-points. The Decision-Maker also provided an interface for the experimenter to interactively control which derived measures or trends were displayed at a given time and what decision criteria set-points were in effect. A separate PC served as a scrolling display of the incoming EEG and EOG channels and stored these raw data on disk for retrospective analyses.

TASK ENVIRONMENT

As a task environment for the present test-bed, a low-fidelity aviation simulation was chosen. This PC-based simulation, called Window/PANES (Workload/PerformANcEe and Simulation) was developed by the Rotorcraft Human Factors Research Branch at NASA Ames Research Center (Ms. Sandra Hart, Manager). Window/PANES provides an environment in which multiple, concurrent discrete and continuous tasks can be presented. Although the displays represent the flight characteristics of a light aircraft, no knowledge of flying is necessary for a subject to learn how to perform the task. The software is nicely designed to support the experimenter in developing scenarios, to log performance and task condition data to disk in real-time as the subject performs the scenario, and to support the experimenter's retrospective analysis of the data.

The display presented on the PC screen has four fixed windows: (1) a graphic display of commanded and current speed, heading, and altitude presented in a "heading-up" orientation; (2) a north-up map which can depict geographical features, the flight path, the aircraft's position on the flight path, and additional information added for experimental purposes; (3) one, two, three, or four gauges presented in analog or digital form that can be labelled and scaled according to experimenter-defined specifications; and (4) an area in which alphanumeric messages can be displayed. These messages can be used to instruct or inform the subject about the scenario, or they can be used to present stimuli in the context of a secondary (or tertiary) task, in order to provide additional measures of performance. The content of alphanumeric messages, gauges, and objects on the map can be either related to or independent of the primary manual control task. A response box providing for the subject's inputs contains a two-axis joystick (fore/aft: altitude, right/left: heading), a vertical slide potentiometer (fore/aft: speed) and response buttons that can be assigned different meanings depending on the structure of a particular scenario.

The behavior of all aspects of the display and task that are not under the subject's control are dependent on a script file which specifies the commanded flight path, the significance and dynamics of

Configuration of the Test-Bed System

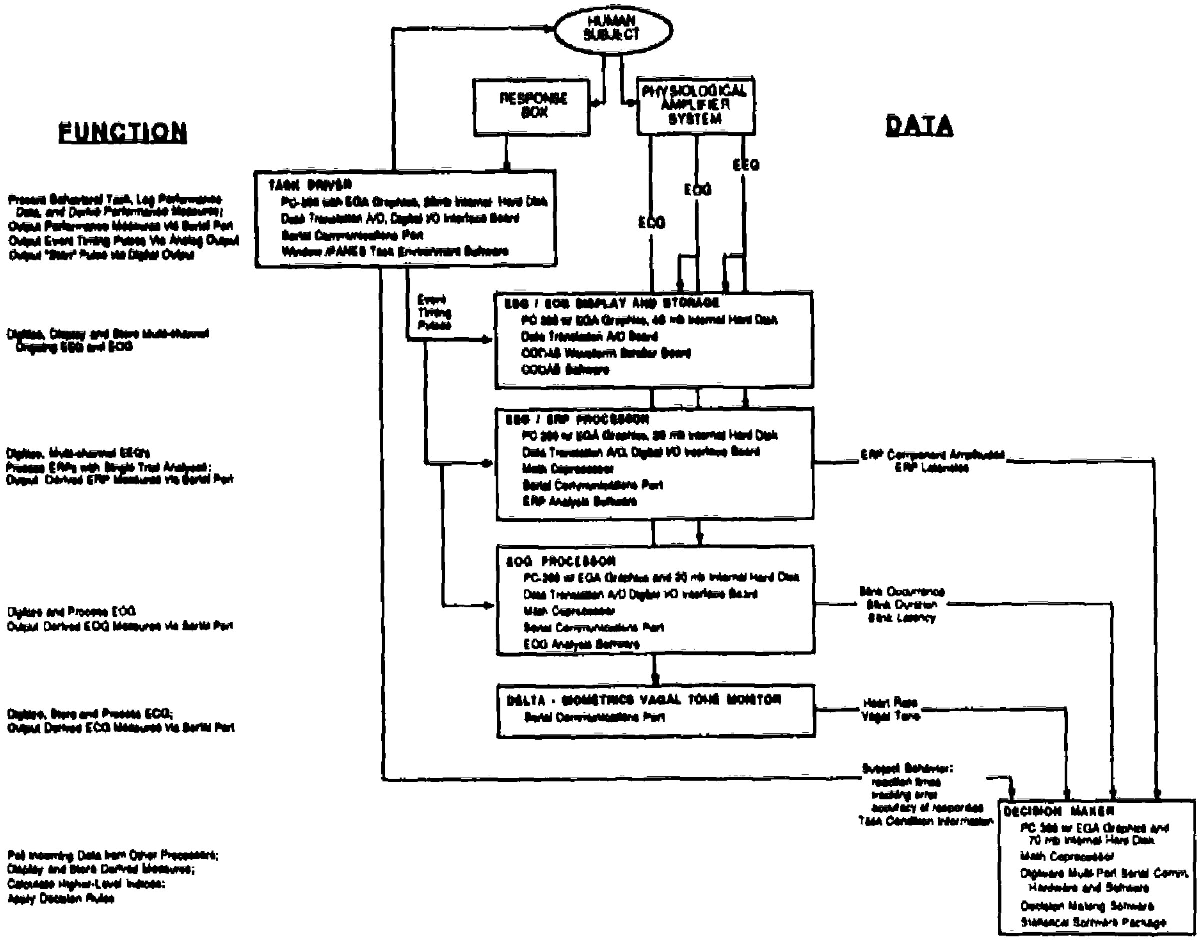

Figure 1 -- A schematic overview of the test-bed system configuration. The hardware components for each subsystem, which in most cases is a separate IBM-compatible PC, are shown in the boxes. The functions of each subsystem are shown on the left side of the figure and the derived measures that are transmitted by each subsystem to the Decision-Maker are shown on the right. The directions in which information flows through the test-bed are indicated by the arrows.

each gauge, the appearance of alphanumeric information, and the discrete responses anticipated from the subject. Script files are prepared by the experimenter in advance and are not modified by the subject's responses during a flight. Data files which combine the "condition" information in the script file with the subject's performance (speed and accuracy of responding) are logged to disk at regular intervals for retrospective analyses.

We found the Window/PANES task environment to be extremely flexible, readily usable, and well-configured for the present research purposes. Figure 2 illustrates the information flow through the "Task Driver" Processor in the test-bed, on which the Window/PANES software was run. The behavioral performance measures of interest (tracking error, response time and accuracy for discrete stimuli and abnormal gauge changes) were captured as they became available, time-stamped, and then output periodically via a serial port for use as one set of inputs to the Decision-Maker. A digital output signal was sent to the individual data processors in the test-bed in order to provide a common time marker for the start of the scenario. Analog output signals (D-to-A) were sent to the ERP and EOG processors to code the occurrence of a task-relevant event (stimulus) of interest.

ECG PROCESSOR

A Delta-Biometrics Vagal Tone Monitor (VTM) was used as the ECG processor. This is a commercially available system that calculates heart rate and vagal tone from an ECG signal. Vagal tone refers to a derived measure of heart-rate variability that quantifies respiratory sinus arrhythmia and which avoids some of the statistically untenable assumptions of power spectral analyses applied to ECG inter-beat-interval (IBI) data (see 6). Vagal tone appears to be quite sensitive to fluctuations in attention and cognitive load (e.g., 7, and unpublished data of our own). Figure 3 illustrates the information flow through the ECG Processor in our test-bed. The VTM was configured to run in its ten-second turn-around mode. Thus, it took ten seconds of amplified ECG from chest electrodes, screened

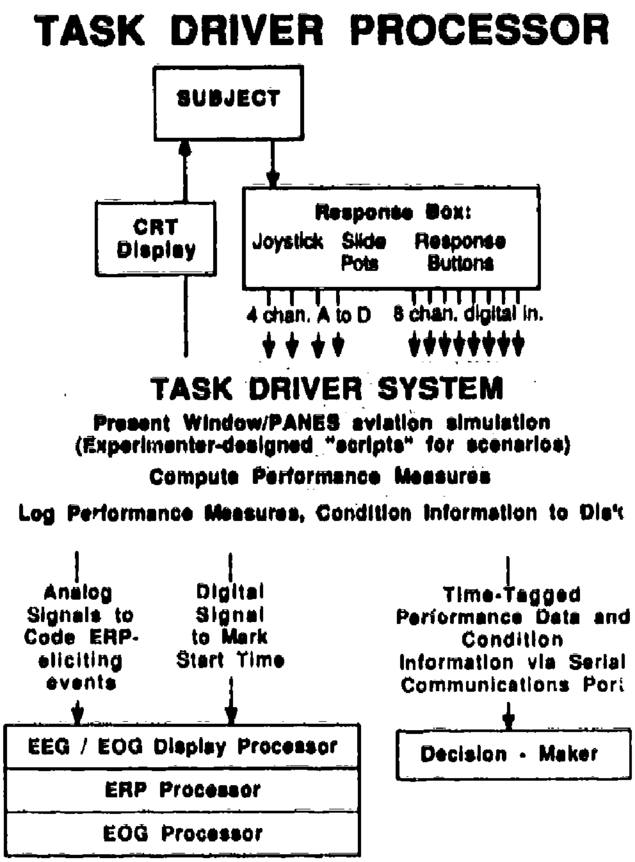

Figure 2 -- Information flow through the Task Driver Processor.

it for artifact, detected the R-waves in the ECG, calculated IBIs, detrended the IBI time series to filter out frequencies unrelated to respiratory sinus arrhythmia, and calculated heart rate and vagal tone from this corrected time series. These derived measures, along with a time-stamp, were output (approximately once every ten seconds) over a serial interface for use as another set of inputs to the Decision-Maker.

EOG PROCESSOR

EOG was amplified by conventional means from sites above and below one eye. Figure 4 illustrates the information flow through the EOG Processor in our test-bed. Five second segments of ongoing EOG were processed in a double buffering scheme. As one five-second period of data was digitized and stored in direct access memory, the preceding five-second's worth of data was processed. The buffer to be processed was digitally filtered and then subjected to an algorithm that applied various experimenter-defined criteria to detect the occurrence of a blink. These criteria involved segments of the EOG waveform that rose and fell by a pre-determined voltage within a pre-determined time period. Once a blink had been detected, it was time-stamped relative to the digital pulse received from the Task Driver at the beginning of the scenario, its duration was estimated from the rise and fall times that were detected by the pattern recognition routine, and the latency of its peak was determined relative to the last analog event-marker received from the Task Driver. These derived measures were output asynchronously (i.e., only after a blink had been detected) over a serial interface for use as another set of inputs to the Decision-Maker.

ERP PROCESSOR

EEG was amplified by conventional means from four scalp sites (Fz, Cz, Pz, and Oz in the International Ten-Twenty System). Of primary interest were several endogenous components of the ERP -- the N200, P300, and Slow Wave, all of which have been shown to reflect cognitive processing (see 8). Approaches for extracting ERPs from the ongoing EEG had been explored on a previous project (unpublished as yet) and the usefulness of the Vector Filter developed by Gratton, et al. (9, 10) was confirmed. For the present feasibility demonstration, it was assumed that the timing of the eliciting stimuli were known to the data processing system. Thus the present ERP components were extracted from ongoing EEG by applying a relatively simple search algorithm to an appropriately filtered segment of multi-channel EEG, time-locked to the events of interest that occurred on the Task Driver.

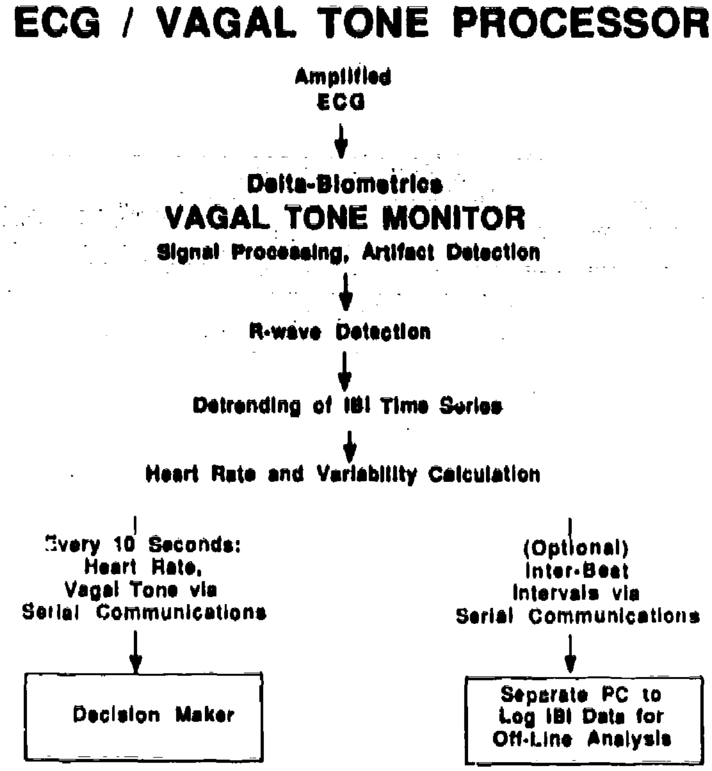

Figure 3 -- Information flow through the ECG/Vagal Tone Processor.

Figure 5 illustrates the information flow through the ERP Processor in our test-bed. The ERP Processor functioned analogously to the EOG Processor, except that instead of searching the incoming five-second buffers for blinks, it searched the event-marker channel for the occurrence of an event of interest. Having found one, it time-stamped the occurrence relative to the digital signal received from the Task Driver at the beginning of the scenario. The EEG was then digitally filtered and a weighted combination of the data across the various scalp sites was derived for each component of interest, using the Vector Filter. Peaks in these weighted combination waveforms were identified within certain latency epochs, and the peak amplitudes and latencies were calculated. These derived measures were output over the serial interface for use as another set of inputs to the Decision-Maker.

DECISION-MAKER PROCESSOR

Information flow through the Decision-Maker is shown in Figure 6. As mentioned previously, the Decision-Maker received derived performance measures from the Task Driver, ECG Processor, EOG Processor, and ERP Processor, all via serial communications. The Decision-Maker polled and stored these incoming data and implemented some simple pattern recognition algorithms to allow the triggering of "cautions and warnings" when certain measures exceeded pre-selected set-points. The Decision-Maker also provided an interface for the experimenter to interactively control which derived measures or trends were displayed at a given time and what decision criteria set-points were in effect. There were two primary display modes provided by the Decision-Maker -- a "trends" display on which various combinations of selected measures could be called up, and a "current status" display showing the values of all derived measures at the current "slice" in time.

VALIDATION OF ALGORITHMS AND EXPERIMENTAL MANIPULATIONS

There are several aspects to the validation of the present test-bed. One aspect of validation has to do with the choice of physiological measures and the quality of the present implementation of the real-time analysis algorithms. That is, do the indices chosen lend themselves to real-time analysis and, if so, do the present algorithms perform as intended? Another aspect of validation has to do with the sensitivity of these measures to task manipulations presented in the operational context of interest. Are these measures, viewed in appropriate combinations, sensitive to task difficulty manipulations that affect performance in meaningful situations? Finally, even if the above questions can be answered in the affirmative, there may be an issue regarding the usefulness of the test-bed. Does this test-bed approach lend itself to studying research issues and aviation design problems that could affect the design of next generation aircraft or other complex man-machine systems?

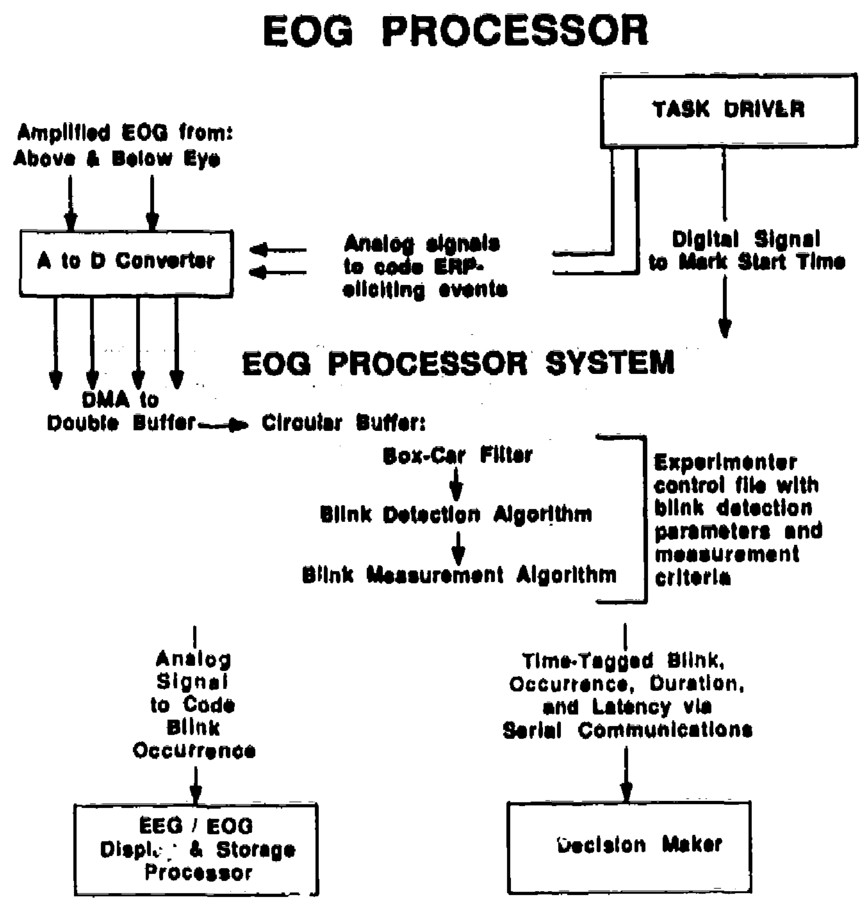

Figure 4 -- Information flow through the EOG Processor.

The present scope of work did not allow a thorough examination of all these issues, and what test results have been obtained can not be presented here in any detail. However, as a proof-of-concept, the present test-bed implementation has proven to be very encouraging. The validation testing that has been conducted to-date can be summarized as follows:

o The Window/PANES task difficulty manipulations were effective in that they were associated with reliable changes in the behavioral measures examined. These behavioral changes were readily apparent when data were averaged over several minute blocks, as in a conventional analysis. Moreover, these behavioral trends were usually apparent in the data transmitted to the Decision-Maker, particularly when the task manipulation was a fairly dramatic one.

o In that the Vagal Tone Monitor was used in its commercially available configuration, which has been thoroughly tested by the manufacturer and used by us on previous projects, there was no need to validate the accuracy of its output. However, an important aspect of the present validation was an examination of the extent to which heart rate and vagal tone measures, based on ten-second segments of ECG data, reflected manipulations of the Window/PANES task. While there is obviously some "noise" to be expected in examining such short segments of ECG, the more dramatic task changes were associated with reliable trends in vagal tone (i.e., an inverse relationship between task difficulty and vagal tone).

o The EOG data processing algorithm was validated by examining its performance with simulated EOG data and by comparing the algorithm's handling of actual EOG with a retrospective visual inspection of stored raw data. The derived EOG measures have proven to be somewhat sensitive to task manipulations, although it is expected that more dramatic changes would be apparent in continuous performance scenarios that put a premium on vigilance and (the warding off of) visual fatigue.

o The ERP data processing algorithm was likewise validated with simulated EEG/ERP data and with previously recorded data from a standard "Oddball" task (e.g., see 8). The ability to extract single-trial estimates of ERP amplitude and latency which mirror the differences seen in conventional average ERPs has been impressive. However, the sensitivity of these waveforms, whether averaged or single trial, to subtle task manipulations in the Window/PANES environment has not been impressive to-date. This may, of course, be due to the task scenarios used thus far.

o The present implementation of the Decision-Maker has proven to be very useful for both monitoring the course of data collection in real-time and examining relationships among the various derived

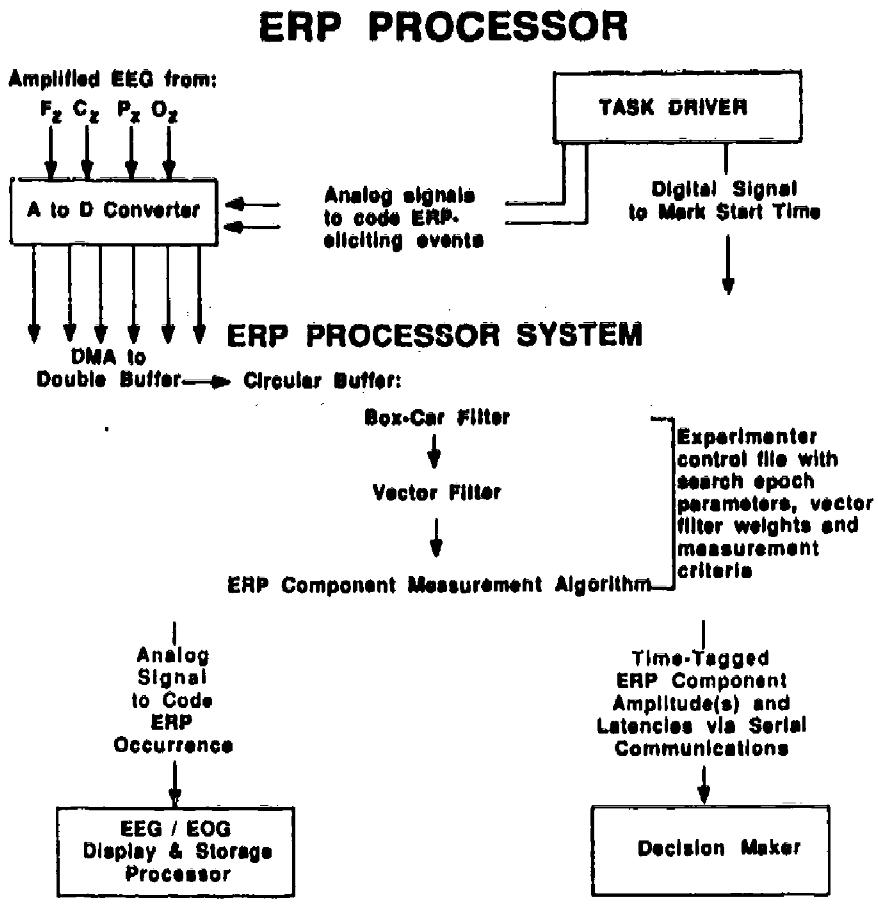

Figure 5 -- Information flow through the ERP Processor

measures retrospectively. Much more remains to be done in the way of optimizing the decision rules based on the available derived measures.

CONCLUSIONS AND FUTURE DIRECTIONS

In most respects, the performance of the present test-bed has been very encouraging. The validation results obtained to-date suggest that we now have a reasonable ability to detect changes in the derived measures of interest "on the fly." The test-bed ran successfully in near "real-time" -- i.e., with lags of approximately five seconds in the EOG and ERP measures, a lag of approximately ten seconds in the ECG measures, and a lag of approximately one second in the behavioral measures. No serious attempt has yet been made to optimize the buffer lengths that underlie these lags, and it is expected that significant reductions will be possible in these turn-around times. Of course, the approximation to real-time that is achievable will be highly dependent on the speed of the processors on which the algorithms are implemented. The usefulness of the present combination of measures was suggested by an encouraging ability to infer changes in task difficulty of the Window/PANES task. This inference ability has thus far only been examined with parameters for the various pattern recognition algorithms being tailored to the individual subject (not an unreasonable constraint in systems that will be operated by a relatively small group of highly trained specialists). Furthermore, the initial testing conducted to-date has concentrated only on rather dramatic manipulations in task difficulty.

Much more needs to be done in examining the performance of this test-bed and in optimizing the parameters used in the pattern recognition algorithms and decision rules. However, the present implementation has confirmed the feasibility of the approach and suggested the usefulness of the test-bed for future research on dynamic man-machine interactions. Potential future directions for the use of this test bed include the following:

- Further validation of the usefulness of the present behavioral and physiological measures. These efforts should include additional systematic collection of empirical data, as well as more fine-grained manipulations in task difficulty and subject status (e.g., sleep deprivation, drug effects, continuous performance challenges).

- Using the test-bed to develop effective decision rules for inferring operator mental status. This

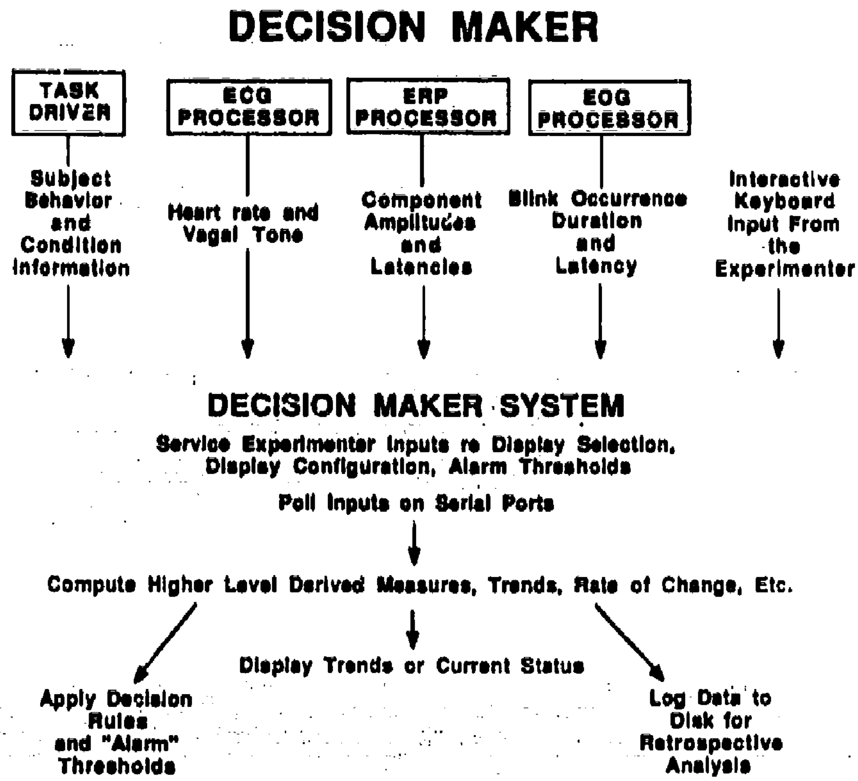

Figure 6 -- Information flow through the Decision-Maker Processor.

effort should explore inference rules based on contingencies among the measures and the generalizability of these rules within and between test subjects.

- Integration of test-bed functions into a single, multi-tasking workstation. This integration effort should include attempts to optimize the real-time algorithms and an exploration of alternative designs for implementing distributed processing approaches that are analogous to those achieved with the present multi-processor configuration.

- Finally, a number of uses are foreseen for the present test-bed in facilitating future research and development on the role of the human operator in automated and semi-automated systems. The test-bed should lend itself to studies of "closed-loop" decision-aiding, dynamic man-machine task allocation, and computational approaches to recognizing operationally significant patterns, across time, in multiple performance measures.

REFERENCES

(1) Orlebeke, J. F., Mulder, G. & van Doornen, L. J. P. (Eds.) Psychophysiology of Cardiovascular Control. New York: Plenum Press, 1985.

(2) Bauer, L. O., Goldstein, R., & Stern, J. A. Effects of information processing demands on physiological response patterns. Psychophysiology, 29, 1987, 213-234.

(3) Donchin, E., Kramer, A. & Wickens, C. Applications of brain event-related potentials to problems in engineering psychology. In M. G. H. Coles, E. Donchin, & S. W. Porges, (Eds.), Psychophysiology: Systems, Processes, and Applications, New York: Guilford, 1986, 702-718.

(4) Horst, R. L., Mahaffey, D. L., Munson, R. C. Brain-wave Measures of Workload in Advanced Cockpits: The Transfer of Technology from Laboratory to Cockpit Simulator, 1989, NASA Contractors Report 4240.

(5) Horst, R. L. An overview of current approaches and future challenges in physiological monitoring. In J. R. Comstock, Jr. (Ed.), Mental-State Estimation -- 1987. 1988, NASA Conference Publication 2504, 25-42.

(6) Porges, S. W. Respiratory sinus arrhythmia: An index of vagal tone. In J. F. Orlebeke, G. Mulder, & L. J. P. van Doornen (Eds.), Psychophysiology of Cardiovascular Control, New York: Plenum Press, 1985, 437-450.

(7) Dellinger, J. A., Taylor, H. L., & Porges, S. W. Atropine sulfate effects on aviator performance and on respiratory-heart period interactions. Aviation, Space and Environmental Medicine, 1986.

(8) Donchin, E., Ritter, W. & McCallum, W. C. Cognitive psychophysiology: The endogenous components of the ERP. In E. Callaway, P. Tueting, & S. Koslow (Eds.), Event-related Brain Potentials in Man, New York: Academic Press, 1987, 349-412.

(9) Gratton, G., Coles, M. G. H., & Donchin, E. A procedure for using multi-electrode information in the analysis of components of the event-related potential: Vector filter. Psychophysiology, 26, 1989, 222-232.

(10) Gratton, G., Kramer, A. F., Coles, M. G. H., & Donchin, E. Simulation studies of latency measures of components of the event-related potential. Psychophysiology, 26, 1989, 233-248.

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INTELLIGENT ASSISTANT SYSTEMS:
AN ARTIFICIAL INTELLIGENCE APPROACH TO DETECTING PERFORMANCE DEGRADATION AND PILOT INCAPACITATION

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SUMMARY

This paper presents an artificial intelligence approach to detecting performance degradation and pilot incapacitation. It discusses the motivations for Intelligent Assistant Systems in such situations. The problem of constructing procedures is shown to be a very critical issue. In particular, keeping procedural experience in both design and operation is critical. We suggest what artificial intelligence can offer in this direction, and present the concept of Integrated Human-Machine Intelligence. Some crucial problems induced by this approach are discussed in detail. Finally, we analyze the various roles that would be shared by both the pilot and the intelligent assistant system.

PREFACE

Human-machine interaction is certainly one of the "hot" topics of the last decade of this century. Aeronautics has been a very privileged field of investigation in this regard. This is because end-users, namely pilots, have been actively involved in the progressive evolution of the systems they control. The concept of Integrated Human-Machine Systems (IHMSs) is clearly pertinent in aeronautics. Pilots are functional components of aviation systems, contributing to the overall performance of the system.

The need for more and more performance, reliability, and accuracy in modern missions increased the automation and pushed pilots' limitations towards their extreme boundaries. In the near future, a pilot will have to share intelligence. Obviously, machine intelligence will not be comparable to human intelligence. However, it will take care of a lot of tasks which were originally allocated to pilots. Humans and machines will have to share responsibilities and perform complementary tasks. Machines are very good at performing routine tasks. However, since it is difficult to design machines that can handle unexpected situations, humans will remain in the control loop. But, if humans remain in the control loop, they will still be subject to performance degradation (in particular, making errors) and incapacitation.

An IHMS can be viewed as a multi-agent interactive system. In this paper, we present a description of the various types of interactions in such systems. But what happens when an agent fails ? If one of them (human or machine) fails, could we assume that the other will maintain the safety of the whole system in a reasonable way ? Probabilities of failure per flight hour are very small for present aircraft (lower than 10^{-7}). Certification criteria are more and more severe. However, in military missions, when an aircraft is in a difficult situation, e.g., low altitude flight in enemy territory or attacked by the enemy army, it may happen that the machine fails. In this case, is there a "good" recovery procedure ? Manual control is generally excluded. Furthermore, there is no computer able to carry out on-line reasoning taking into account situations not identified in advance, which will be able to provide a solution in real-time. The only possibility is to recall typical (analogous) cases already tested and recorded during previous simulations or real flights. These recovery procedures could be implemented in cooperation with pilots. Humans are most likely to fail for various reasons due to unconsciousness, excessive workload, stress etc. In this case again, previously stored procedures are still the most realistic solution. These procedures can be used either to monitor and "understand" what the pilot is doing (prevention), or to provide an active aid in case of performance degradation or pilot incapacitation (recovery).

Intelligent assistant systems (IASs) constitute a class of computer programs (Boy, 1990a) that can guide access to, and apply procedures derived from experience, and can assist in the formation of new procedures through reasoning by analogy. They are knowledge-intensive sources for intelligent assistance, designed to mediate interactions with the machine and perform some of the required intelligent functions. The primary goals of this paper are to (1) present the state of the art of IASs in aerospace systems, (2) determine factors necessary to advance the state of the art, (3) reveal research and real-world applications needs as well as opportunities for the future, and (4) form an interdisciplinary core of physicians, physiologists, computer and cognitive scientists, engineers and designers for future communication and cooperation on IHMS.

1. MOTIVATION FOR INTELLIGENT ASSISTANT SYSTEMS

Both industry and government researchers in aerospace are in agreement with the emphasis that artificial intelligence (AI) can be viewed as a technical base with great potential to enhance productivity and safety, and help them cope with the demands of increasingly complex technology and high workload.

A special kind of AI system is emerging which specifically recognizes the design constraints inherent in the cooperation of humans and AI-based aids (Boy, 1987). This kind of system has been called either an Operator Assistant system or an Operator Associate system depending on the level of autonomy it has. At the workshop on "Integrated Human-Machine Intelligence in Aerospace Systems" (Shalin & Boy, 1989) held during the 1989 International Joint Conference on Artificial Intelligence, it was concluded that a better name might be "Intelligent Assistant System". However much work remains for realizing the Intelligent Assistant concept. Intuitive models of operator performance will not be sufficient. The necessary models will require multidisciplinary research in human perception and reasoning not obtainable within the narrow framework of the present state-of-the-art in computer science. They are likely to require the full range of disciplines represented by the participants at this NATO Symposium. Furthermore, many major government and industry funding sources have recognized the challenge of building intelligent assistants, as evidenced by the support for various national "Pilot Associate" programs.

This paper propose an alternative approach to automation in slightly degraded as well as extreme situations. According to this alternative, human beings take on the role of task designers or perhaps remote monitors, while automated systems with some problem solving capability become actors on the environment also. Thus, human beings will not be the only problem solvers. They will coexist with artificial intelligent agents on a cooperative basis. This cooperative relationship is based on the construction and use of procedures.

2. WHAT ARTIFICIAL INTELLIGENCE HAS TO OFFER

A current engineering idea is to create a system which supports the human operator in performing the task rather than to model and then automate human cognitive processes. Abbott (1989) identified three categories of use of AI in IHMSs. The first is the use of AI in the automation of a particular task, such as onboard monitoring, windshear detection, or retrieval of a recovery procedure in time. AI methods and tools can be very effective for these tasks because they involve heuristic reasoning, search through large information spaces, and reasoning about physical systems in operation. In this case AI is used not because it mimics the human's thought processes but because it is the most appropriate tool for the job.

The second category mentioned by Abbott involves the control of multiple onboard systems. In situations where time is critical, AI can improve the efficiency of some computations and even the organization and coordination of several computations. AI systems can insure that the high priority computations are completed in time. The IAS architecture should support temporal and nonmonotonic reasoning, interrupt handling, methods for handling noisy data, and trend analysis.

The third category concerns interfaces between the aircraft and the pilot. If we want to get adaptive interfaces, they constantly need to assess the situation and the pilot's current needs in order to provide the appropriate information in an appropriate manner.

In the specific case of extreme flight situations, our contribution focuses on (1) iterative procedure acquisition, and (2) reasoning by analogy. The design of procedures is currently based not only on the design rationale but also on pilots requirements and suggestions. AI can provide more automation of this process of designing procedures. In the first place, design rationale and alternatives can be captured during the aircraft design process. A similar approach has been taken for the design of the Space Station Freedom (Boose et al., 1990). The way this kind of knowledge is used afterwards depends on the tasks requiring it. Even if such documentation is very rich, there are "good" ways to search in it to retrieve appropriate information. Some AI techniques are very appropriate to tackle and partially solve these problems of search in large databases. Procedures are also built from such design knowledge. If this knowledge is more easily accessible, then it will be easier to build procedures. Building procedures is an iterative process with pilots continually giving criticisms and recommendations for better procedures. One of the main tasks assigned to operations engineers involved in procedure writing is to modify already existing procedures from such recommendations. The underlying process is analogy. Faced with a new event, a pilot tries to match this event to the description of an existing procedure. He will try to use the available procedure as much as he can, but will then have to use other knowledge, generally common sense knowledge. Procedures are upgraded by operations engineers in the same way. They take anecdotes from the pilots on situations and try to modify existing procedures to include the corresponding situations in their descriptions. If this process of procedure management and maintenance is systematized and handle by computers, it will be possible to generate more appropriate procedures in more extensive situations. This iterative process will lead to preservation of operational knowledge, and generalize some situations and their attached recovery procedures. A method has been proposed to handle such a procedure acquisition process (Boy, 1990b). Obviously, this approach contributes to better handling of extreme situations. This is because more recovery possibilities will be provided and available onboard. They can be tested both in simulation and real flights. Their tests will improve them and generate new cases, and then new procedures. The decision to automate procedure execution is a difficult business and we will leave it for the discussion.

3. TOWARDS A CONCEPT OF INTEGRATED HUMAN-MACHINE INTELLIGENCE

Work has already been done to tackle the difficult problem of real-time "intelligent" process control (Lusk et al., 1983; Moore et al., 1984). This paper presents a more formal approach to IASs. Safety requirements and human error problems lead to the definition of *three possible kinds of IASs*: (1) interactive systems to tolerate human errors (Amalberti, 1986; Norman, 1981; Roscoe, 1980) in standard situations, (2) workload relief systems in standard situations with high workload, and (3) interactive aids for problem solving in abnormal situations with high workload (Amalberti, 1986). The first and second types can easily be implemented using classical programming systems or "conventional" expert systems. The third type stresses the need for a deeper description of both design and operational knowledge. This research effort should lead to an appropriate architecture for such IAS. This paper focuses on this third type.

A model called SRAR (Situation Recognition and Analytical Reasoning) has been already developed for representing human problem solving in dynamic and interactive environments (Boy, 1987). This model was derived from experimental results on a diagnosis assistant system developed at NASA (Boy, 1986) and a previous research effort on commercial aircraft certification (Boy, 1983). Our model is an alternative to Genesereth (1982) and Clancey (1984) models for tackling the difficult problem of integrated human-machine intelligence (IHMI), i.e., a model based on a knowledge representation appropriate to the implementation of the SRAR model. This representation is called *block* representation. It was designed to improve operational knowledge acquisition and extend previous work on procedure representation (Georgeff & Lansky, 1986)

IHMI design can be seen as (1) parsing the operator's actions in order to understand what he is doing, and (2) providing him with the appropriate level of information and proposing appropriate actions or procedures for him to execute. The overall underlying model is presented in figure 1. Arrows represent information flows. This model includes two loops: (1) a short term supervisory control loop, and (2) a long term evaluation loop. The technical domain knowledge base includes descriptions of various objects relevant and necessary in the domain of expertise. The operational knowledge base includes available procedures necessary to handle various already-encountered environmental situations. The knowledge acquisition knowledge base includes what is necessary to know for upgrading operational procedures.

4. ISSUES IN INTELLIGENT ASSISTANT SYSTEMS

As the main goal is to design and iteratively refine procedures, there are some issues inherent in this approach which have to be discussed. Do we need cognitive models to build and refine these procedures ? The application of such procedures will depend on their understandability and thus user interfaces become critical. How can we carry out the knowledge acquisition process ? Is there a better way to represent procedures ? What kind of issues are raised by intelligent assistant architectures ? AI techniques have been implemented on very academic problem so far. Are they robust enough to handle real-world applications like the ones we are discussing ?

4.1. Cognitive Models, Knowledge Acquisition and Representation

The goal is not to design cognitive models for building human clones, but: (1) to understand human-AI systems interaction, (2) use operator models in system design, e.g., designing intent recognition mechanisms (Geddes, 1985, 1986; Shalin et al., 1988), and (3) design user interfaces with AI-systems. The users of a specific intelligent assistant system for an aerospace application may not all share the implicit model of expertise that has been incorporated into the system. Many domains, such as tactical warfare, are rife with individual differences because of the lack of a standardized procedure below a certain level of analysis. These differences could have a major impact on the knowledge base of the intelligent assistant system. This compounds the knowledge acquisition problem, and indicates the need for automated knowledge acquisition. These differences may impact the functionality of the system, for example, the depth of explanation, user monitoring, and instruction required.

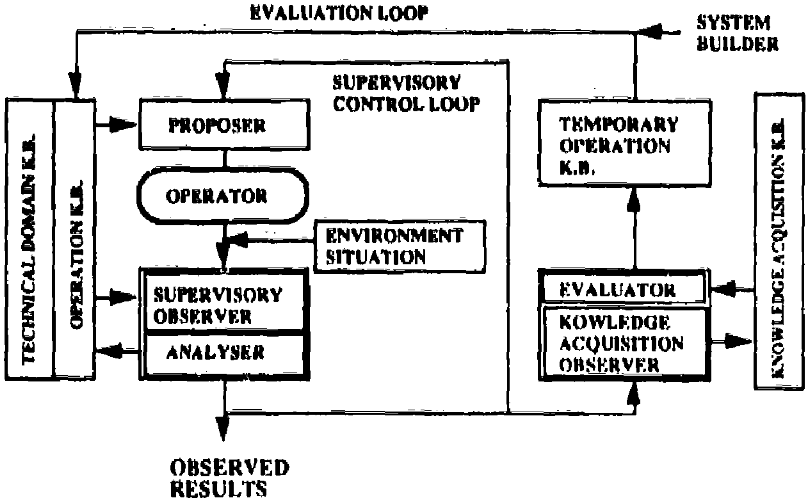

Figure 1. An Integrated Human-Machine Intelligence model

Knowledge acquisition, that is eliciting the expert's knowledge about the task domain, is generally accepted as a significant bottleneck in system development. Knowledge is, however crucial to the success of IASs. An IAS will not discover new knowledge by itself in real-time real-world situations. And even if some AI scientists argue that discovery can be handled by some artificial intelligence systems, these system have to be guided and "interpreted" by the scientists themselves. This is clearly not currently possible in high workload situations where the time-pressure is great. Thus, acceptable systems are limited to a particular class: procedural systems. By procedural, we mean systems that are based on explicit procedures, eventually using some very well-structured declarative knowledge. The problem in critical situations is not to build procedures from scratch, but to use procedures already tested and adapted to the current situation. The artificial intelligence problem is then to collect these procedures, and to refine them incrementally with experience. The real problem is to capture both design knowledge and user knowledge to build the most adapted procedures. These procedures are initially appropriate in particular situations, but after several simulations or real missions they can be classified into more general classes of situations. Knowledge acquisition will consist of following the IHMS from its design to its everyday use. We view knowledge acquisition as an incremental process (sometimes a trial and error process) improving both the domain knowledge accumulated through experiments and the meta-knowledge useful for elicitating and ratifying this knowledge. Furthermore, we claim that the activity of knowledge acquisition can provide important insights towards a possible theory of cognition.

In all cases, it seems that goals (and sub-goals), plans (i.e., procedures), and situations (or events or states) are the three most common ingredients of the knowledge representation currently in use. The expression "situated actions" has been the focus of recent AI contributions (Suchman, 1987; Drummond, 1989). However, if the word "context" is always a major concern, very few convincing definitions of it have been explicitly given. Time and exceptions (abnormal conditions) are also major concerns in the knowledge representation issue of IHMS research. They are leading to investigations in the representation of uncertainty, imprecision, and incompleteness.

4.2. Compatibility of An Intelligent Assistant System with the Pilot

As already noted, at present IHMI research is dominated by procedural tasks to be performed on engineered systems in non-deterministic environments. Though controversial, a need for compatibility with the pilot has potentially far-reaching consequences on the system inputs/outputs and processing (Shalin & Boy, 1989).

Inputs/Outputs (Communication) Compatibility—Certain task environments (e.g., weightlessness, high G's, protective gear, high workload) restrict human input, such as text typing. This kind of environment is ripe for intelligent interfaces endowed with user intent recognition. There is also concern for cognitive compatibility. This is evidenced by the development of communication languages that are adequate for the task and correspond to human reasoning about the task domain. A final consideration of man-machine communication is system output. In particular explanation facilities are often controversial. In aircraft cockpit, for example, explanation should be reduced to a minimum, especially when the control frequency is very high. This does not mean that explanation should be absent, the cockpit must be self-explanatory at each instant and include very polysemic displays.

Processing Compatibility—The need for incremental development, and possibly incremental modification suggests a requirement for compatibility at the level of processing, so that users can provide direct feedback on system functionality. To enhance user confidence, processing might include standard human capabilities, such as reasoning about the consequences of its recommendations. An additional consideration for processing compatibility is user awareness of the boundaries of system reliability. Any automation in reactive environments may require systems to be straightforward extensions of the operator's perceptual and cognitive abilities, as there is simply not enough time for any extensive on-line analysis of the system by the user.

Real-time AI— The real-time AI issue deals not only with the computation speed, but also with resource allocation, cooperation, and procedure interruption. As the data is uncertain, imprecise and incomplete, the integration of nonmonotonic logic in an intelligent assistant system is critical. This integration should be done pragmatically and incrementally refined by experimentation. Discussions on this issue lead to four possible software architectural tools: conventional programming will still be useful, e.g., for implementation of microscopic details; blackboard architectures are useful for implementing cooperative and opportunistic interaction (Nii, 1986): agents architectures (as extensions of object-oriented languages) will be interesting for multi-agent cooperation when internal models of the various utterers are available (e.g., in intent recognition); hypermedia (Conklin, 1987) provide explicit external representation of various agents able to interact between each other (i.e., message passing).

Knowledge-Based System Validation—The state-of-the-art in expert system validation techniques is not very well advanced at present. Methodologies have to be designed, developed and tested. Like knowledge acquisition, validation is an incremental process. Moreover, knowledge acquisition and validation can be seen as twin processes in knowledge-based system design. Certainly, inclusion of potential end-users in the design loop is one of the best solutions for incremental validation. The validation of knowledge-based systems might be compared to the certification of airplanes, at least in terms of complexity.

4.3. Real-World Applications and the Automation Issue

The present field of investigation is experimental. Theoretical knowledge representations are not coming from pure introspection, but from experience in the domain and from experimental protocols. Application domains are picked in real-world environments and focus on the decision making, diagnosis, planning and control of engineered systems. They are generally bounded and procedure-driven. For these reasons, current research issues are concerned with undeterministic deviations around procedures (deterministic blocks of knowledge). At this point, the most important difficulty is related to situation assessment. Humans are good situation assessors when they are really in the control loop. However, it is very difficult to elicit their situation assessment mechanisms and strategies. They get very sophisticated situation patterns by experience. Machine learning (Kodratoff, 1989) research provides a set of techniques which can be used for re-creating such patterns by experimentation. As far as situation assessment is concerned (both by a human operator and an intelligent assistant system), the main difficulty in intelligent assistance is summarized by the three following issues: (1) When has information to be presented ? (2) What content should it include ? (3) What format does it require ?

Experience in real-world applications should provide a taxonomy of knowledge processing activities from the design activity to operations. As already discussed, from the difference in types of explanation required in different activities, it follows that the types of recommendations given to operators or designers are quite different. The problem comes when the level of investigation changes, e.g., when an operator following religiously a set of procedures will have to investigate a new unexpected situation involving the creation of appropriate procedures; he/she becomes a procedure designer. This is one good reason why people are still "controlling" "fully" automated machines, they are unique in their ability to handle unanticipated situations. If a non-nominal situation can be anticipated, it could be considered as "nominal" by a system which knows it. Nominal situations are understood as known in advance. However, when an unanticipated situation occurs, the operator must be aware and understand what is going on, i.e , the intelligent assistant system should not mask or distort the real world. This introduces the difficult problem of quality and safety constraints.

Real-world applications bring the dual problem of training versus cognitive ergonomics. One is concerned with the compliance of the human to the machine, and the other one with the compliance of the machine to the human. If the machine does not comply enough then an excessive workload appears on the human operator side. Conversely, if the machine is "too automated" (or autonomous), the human operator tends to loose his/her vigilance. The ideal machine would comply with or complement the cognitive capabilities of the human operator in any situation.

One factor in human-system function allocation is the existence of partitionable tasks between the two decision makers. In addition, overall performance should be optimized by maintaining the best qualities of each in the ultimate allocation. In domains such as Tactical Warfare, there may be a need for a dynamic task allocation between the human and the system. Depending upon the context and demands on the operator, the system may have more or less authority in executing portions of the task. Task allocation may in addition, be affected by policy restrictions on modifying existing operations.

Automation in real-world applications, such as aviation, has already shown the real problem of human errors. Analyses of these errors should bring a new set of recommendations for iterative procedure design and maintenance.

Machines do some things better than humans, e.g., computations. They work on well-formulated problems. They are not inventive. Thus, what does AI bring in the automation issue ? Does AI bring new issues in human-AI system interaction ? Certainly, AI, by its methods, is beginning to support the notion that full automation is no more an issue, i.e., human operators have to be taken into account during the design process (human-centered design) (Woods & Hollnagel, 1987). An important issue raised by AI is that there is a need for a better understanding of interactions between intelligent agents (human and machine). Artificial intelligence and natural intelligence do not match, but there should be a way for "good" cooperation between them. In particular, if one of the actors is "incapacitated", it may happen in the future that the other, in general, will help to recover.

5. HOW WILL THE VARIOUS ROLES BE SHARED ?

In intelligent systems of the future, artificial agents and human operators will both perform intelligent tasks in the context of an integrated system. Each has responsibilities, requires access to resources, and has particular knowledge appropriate to tasks. Some tasks may be done in parallel, others may require results from tasks performed by other agents.

The balance of sharing in intelligent functions can be characterized as a continuum:

Manual ◄—— Interactive ——► Automated

In completely manual and totally automated systems, the user and machine are effectively decoupled. In the intermediate range, where IHMSs lie, the human and artificial agents must interact by *communication*.

When designing integrated systems the designer needs to consider the nature of communication among the agents, human and artificial. The type of interaction depends, in part, on the knowledge each agent has of the others. An agent interacting with another agent, called a partner, can belong to two classes: (1) the agent does not know its partner, (2) the agent knows its partner. The second class can be decomposed into two sub-classes: (2a) the agent knows its partner indirectly (using shared data for instance), (2b) the agent knows its partner explicitly (using communication primitives clearly understood by the partner). This classification leads to three relations between two agents communicating: (A) competition, (B) cooperation by sharing common data, (C) cooperation by direct communication.

In the competition case, the agent is totally ignorant of the existence of other agents. This can lead to conflicts for existing resources. Thus, it is necessary to define a set of synchronization rules for avoiding any problems of resource allocation between agents. Typically, these synchronization rules have to be handled by a supervisor. The supervisor can be one of the partners or an external agent. Obviously, if available resources exceed the requirements of all the agents, conflicts are automatically avoided. In the real world, we do not usually know all these requirements and it is impossible to create physical resources on demand.

In the case of cooperation by sharing common data, the agent knows that its partner exists because it is aware of the results of (at least) some of the partner's actions. Both of them use a shared data base. Agents use and update this data base. An example would be both agents noting all their actions on a blackboard to which each agent refers before acting. This is no longer a problem of resource allocation, but a problem of sharing data which each agent can use as it is entitled to. Agents have to cooperate to manage the shared data base. This paradigm is called a data-oriented system. Such a system has to control the consistency of the shared data. Cooperative relations between agents do not exclude competitive relations. Shared data are generally supported by resources for which the corresponding agents may be competing. In this case, synchronization rules have to deal with resolution of resource allocation conflicts and corresponding data consistency checking.

In the previous cases, the interaction is always indirect. In the case of cooperating by direct communication, agents share a common goal and a common language expressed by messages, e.g., experts in the same domain cooperating to solve a problem.

Human operators do poorly at monitoring tasks if they are not involved in cognitive activity related to the system being monitored. On the other hand, humans are not as good as machines at highly repetitive, complex, or very time-critical tasks. Thus a designer must strike a balance between total user control and autonomous machine control.

Sharing autonomy between humans and machines is very important and poorly understood. In this section, we extend the concept of levels of automation introduced by Sheridan (1984). We will give here a theoretical model of the performance of a simple human-machine system under different levels of autonomy determined by different levels of understanding or knowledge about the human-machine system (figure 2). The horizontal axis represents a continuum of levels of autonomy from "manual control" to "complete automation". The vertical axis represents the performance of the human-machine system. Performance could be related to time, precision of results, costs to solve a given problem or any heuristic criterion appropriate for measuring performance. Each curve of figure 2 corresponds to a level of knowledge the designer has about the task. (In general, better designer knowledge leads to higher performance of the designed system.)

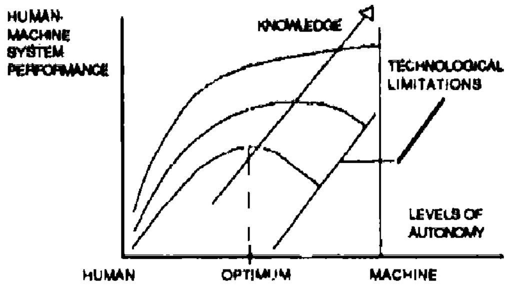

Figure 2. Human-Machine System Performance versus Levels of Autonomy (Boy, 1986).

Following the above model, the performance of the human-machine system increases with the autonomy of the machine, but only until some optimum, after which it decreases. If the autonomy of the machine is further increased, the human operator is likely to lose control of the situation. Note that the level of autonomy can be increased to a certain limit fixed by technological limitations. At present, most engineering projects are developed on these technological limitations, i.e., machines are built as well as possible from strictly machine-centered optimization criteria. In our approach, optimization criteria are centered on the end-user/machine performance. Such an approach necessitates simulations and real-world experimentation. Human-machine system performance optima can be shifted to the right if human operators are very well trained. Globally, when the level of understanding and knowledge increases, these optima shift up and right. Finally, if everything is known about the machine control in its environment, then the corresponding optimum is located on the complete autonomy limit. It has been shown that searching for such performance optima is a good method for acquiring knowledge from experience, i.e., generally we jump from a lower curve to a higher one as we acquire knowledge.

6. CONCLUSION

This paper discusses several ideas and lessons learned through experience in the Human-Machine Interaction and Artificial Intelligence Group at ONERA/CERT, and in the Aerospace Human Factors Research Division and the Intelligent Assistant Group at NASA Ames Research Center. A critical test of this research effort is its utility in industrial applications. Dialogics is currently implementing some of these ideas in real-world situations.

Can we design new onboard capabilities that will improve the safety network to detect performance degradation and pilot incapacitation ? Artificial intelligence introduces new problems. In particular, the problem of cooperation between human intelligence and machine intelligence. A new question is: are we designing tools or assistants ? Will we manipulate physical devices or will we cooperate with smart machines ? Different types of knowledge have to be distinguished: designers, end-users, and maintenance people for instance. The problem of constructing procedures has been shown to be a very critical issue. In particular, it seems crucial that past experience in both design and operation has to be captured and stored, in a corporate memory for instance. This will be useful for generating libraries of operational problems, maintenance, redesign, and even for design of new machines. Design, simulation, and tests should be integrated.

Are we going to cooperate with intelligent assistant systems ? If the answer is no, what do you think the alternative would be ? If the answer is yes, then there is no time to waste for studying intelligent human-machine cooperation.

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REFERENCES

Abbott, K.H., (1989), "Human-Centered Automation and AI: Ideas, Insights, and Issues From the Intelligent Cockpit Aids Research Effort", *Proceedings of the IJCAI-89 Workshop Report on Integrated Human-Machine Intelligence in Aerospace Systems*, Detroit, Michigan, U.S.A., August.

Amalberti, R., (1986), "Human Errors in Some Aeronautics Accidents and Perspectives of Intelligent Aiding", *Proceedings of the First International Conference on Human-Machine Interaction and Artificial Intelligence in Aeronautics and Space*, G. Boy Ed., October 13-14, Toulouse, France.

Boose, J.H., Shema, D.B., & Bradshaw, J.M., (1990), "Design Knowledge Capture for a Corporate Memory Facility", submitted to the *5th Conference on Artificial Intelligence for Space Applications*, Huntsville, May.

Boy, G.A., (1983), "Le Système MESSAGE: Un Premier Pas vers l'Analyse Assistée par Ordinateur des Interactions Homme-Machine", *Le Travail Humain*, Tome 46, 2.

Boy, G.A. (1986), "An Expert System for Fault Diagnosis in Orbital Refueling Operations", *AIAA 24th Aerospace Sciences Meeting*, Jan., Reno, Nevada.

Boy, G.A. (1987), "Operator Assistant Systems", *Int. J. Man-Machine Studies*, 27, pp. 541-554.

Boy, G.A., (1990a), *"Intelligent Assistant Systems"*, book to appear, Academic Press.

Boy, G.A., (1990b), "Procedure Acquisition and Refinement According to Context", NASA Ames Research Center, Moffett Field, CA, U.S.A.

Clancey, W.J., (1984), "Methodology for building an intelligent tutoring system", In W. Kintsch, J. Miller, and P. Polson (Eds.), *Methods for tactics in cognitive science*. Hillsdale, NJ: Erlbaum.

Conklin, J., (1987), "Hypertext: An Introduction and Survey", Computer, September.

Drummond, M., (1989), "Situated Control Rules", *Proceedings of the First International Conference on Principle of Knowledge Representation and Reasoning*, Morgan Kaufmann Pub., Toronto, May.

Geddes, N.D., (1985), "Intent inferencing using scripts and plans", *Proceedings of the First Annual Aerospace Applications of Artificial Intelligence Conference*, Dayton, Ohio.

Geddes, N.D., (1986), "The use of individual differences in inferring human operator intentions", *Proceedings of the Second Annual Aerospace Applications of Artificial Intelligence Conference*, Dayton, Ohio.

Georgeff, M.P., & Lansky, A.L., (1986), "Procedural Knowledge", *Proceedings of the IEEE Special Issue on Knowledge Representation*, 74, pp. 1383-1398.

Genesereth, M.R., (1982), "The role of plans in intelligent teaching systems", In D. Sleeman, J.S. Brown (Eds.), *Intelligent Tutoring Systems*, New York, NY: Academic Press, pp. 137-155.

Kodratoff, Y., (1989), *"Introduction to Machine Learning"*, Morgan Kaufmann Publishers, San Mateo, California.

Lusk E., & Stratton R., (1983), "Automated Reasoning and Man Machine Control System", Proc. of the Ninth Annual Advanced Control Conf., West Lafayette, Ind.

Moore R., Hawkinson L., & Knickerbocker, C., (1984), "A Real Time Expert System for Process Control", Proc. of the 1st Conf. on A.I. Applications, Denver, Col.

Nagel, D.C., (1986), "Pilots of the Future: Humans or Computers ?", *Proceedings of the First International Conference on Human-Machine Interaction and Artificial Intelligence in Aeronautics and Space*, G. Boy Ed., October 13-14, Toulouse, France.

Nii, H.P., (1986), "Blackboard Systems: the Blackboard Model of Problem Solving and the Evolution of Blackboard Architectures", AI magazine, summer 86, p. 38-53.

Norman, D., (1981), "Categorization of Action Slips", Psychological Review, 88, p. 1-15.

Roscoe, S., (1980), "Cockpit Workload, Residual Attention and Pilot Errors", *Aviation Psychology*, Iowa University Press.

Shalin, V.L., & Boy, G.A., (1989), *"Proceedings of the IJCAI-89 Workshop Report on Integrated Human-Machine Intelligence in Aerospace Systems"*, Detroit, Michigan, U.S.A., August.

Shalin, V.L., Perschbacher, D.L., & Jamar, P.G., (1988), "Intent Recognition: An Emerging Concept", *Proceedings of the 2nd International Conference on Human-Machine Interaction and Artificial Intelligence in Aeronautics and Space*, Toulouse, France, September 28-30.

Sheridan, T.B., (1984), "Supervisory Control of Remote Manipulator, Vehicles and Dynamic Processes: Experiment in Command and Display Aiding". *Advances in Man-Machine System Research*, J.A.I. Press, Vol. 1, pp. 49-137.

Suchman, L.A., (1987), *"Plans and Situated Actions. The Problem of Human-Machine Communication"*, Cambridge University Press.

Woods, D., & Hollnagel, E., (1987), "Mapping Cognitive Demands in Complex Problem Solving Worlds", *Int. J. Man-Machine Studies*, 26, pp. 257-275.

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This Symposium reviewed the current status of technological developments as well as philosophical issue which must be addressed.

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