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MOTION SICKNESS, VISUAL DISPLAYS, AND ARMORED VEHICLE DESIGN

PROCEEDINGS OF A CONFERENCE

APRIL 1990

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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CONFERENCE ON WRAPAROUND VISUAL DISPLAYS

January 14-15, 1988
Brandeis University
Waltham, Massachusetts

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Foreword

The Committee on Vision is a standing committee of the National Research Council's Commission on Behavioral and Social Sciences and Education. The committee provides analysis and advice on scientific issues and applied problems involving vision. It also attempts to stimulate the further development of visual science and to provide a forum in which basic and applied scientists, engineers, and clinicians can interact. Working groups of the committee study questions that may involve engineering and equipment, physiological and physical optics, neurophysiology, psychophysics, perception, environmental effects on vision, and treatment of visual disorders.

In order for the committee to perform its role effectively, it draws on experts from a wide range of scientific, engineering, and clinical disciplines. For this study of wraparound visual displays, the working group members were chosen for their expertises in research related to adaptive changes in the visual/vestibular system and for their familiarity with the application of those research findings to the design of electronic displays. They were joined by others interested in this topic at a conference in January 1988 held to exchange ideas.

This report reflects the conference participants' understanding of the changes in viewing conditions that would arise from proposed changes in the design of armored vehicles. It also presents their suggestions for lines of research that would be informative for the selection of design alternatives, with emphasis on the design, location, and use of visual displays.

This report will be of particular interest to those involved in the design of systems in which motion sickness has been a concern and those whose basic research activities continue to strengthen the knowledge base in this area.

Suzanne McKee, Chair
Committee on Vision

Preface

In response to a request from the United States Army Ballistics Research Laboratory, the Committee on Vision established the Working Group on Wraparound Visual Displays. The working group was asked to review the operational requirements of anticipated low-profile armored vehicles and to determine the underlying visual/vestibular research issues relevant to the appropriate design of the visual display system within those vehicles.

To accomplish these goals, the working group convened a small conference to review what is known about motion sickness symptoms arising from the response of the oculomotor system to conflicting visual and vestibular cues. Eight specialists from the fields of visual psychophysics, neuroscience and human factors engineering met for two days at Brandeis University in January 1988. Participants reviewed what is known about research in this area with specific reference to the environmental conditions likely to be encountered in low-profile armored vehicles. They essentially provided a tutorial on the different methodological approaches to visual/vestibular issues relevant to the design of electronic visual displays. The program offered ample opportunity for formal and informal group discussion. The edited proceedings of the discussion, together with an executive summary developed by the working group, are the contents of this report.

In addition to the specialists who participated in the Brandeis conference, a number of people contributed in important ways to the success of this project. Our thanks go to James Walbert and his staff at the U.S. Army Ballistics Research Laboratory, who briefed the working group on several occasions, thereby providing important technical information. And as always, thanks are due to Pamela Ebert Flattau, the committee's study director, who assisted in organizing the effort and in preparing the report, and to Carol Metcalf, the committee's administrative secretary, who provided efficient and helpful support.

Herschel W. Leibowitz
Chair, Working Group on
Wraparound Visual Displays

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Highlights

A theoretical understanding of the underlying causes of motion sickness is important to U.S. Army engineers engaged in the design of visual display systems for use in next-generation armored vehicles. Motion sickness symptoms can lead to spatial disorientation, reduced operational performance, and safety problems. One goal of the conference, then, was to review the latest theories and research findings on motion sickness and visual displays.

Motion sickness symptoms are, of course, adaptive changes of the oculomotor system arising from conflicting visual and vestibular cues. Conference participants discussed a variety of issues related to research on this topic. Highlights of those discussions, which appear in greater detail throughout this volume, are given below:

- Research on simulator sickness may have applications in armored vehicle design. In the vision area, some of the simulator characteristics that have been found to be related to the onset of motion sickness include the field of view, retinal eccentricity, off-axis displays, and head movements. Cases of simulator sickness have been documented with computer-generated imagery and point source lighting, but less frequently with model board systems.
- Vertical movements in vehicles affect the magnitude of the resultant force of gravity, which in turn modifies the position of the eyes. To fixate a target, the operator must override both the vestibular and the ocular responses to the vector forces.
- If an operator must view a display in a bumping, moving vehicle, the vestibulo-ocular reflex (VOR) must be overcome to maintain gaze stability. One possible solution is to build a device to stabilize displays, much like that on naval platforms.
- The correlation between sensed movements and display feedback information is very critical. *Telepresence* essentially tries to maximize the ability of the operator to utilize normal sensory and motor strategies. Important conditions that have emerged thus far that can degrade telepresence

and ultimately preclude adaptation or learning include time delays, noise, and learning/adaptation.

- In stressful situations, information displayed to an operator may need to be redundant. Display concepts that appear promising—but that need to undergo field testing—include pseudoperspective symbolic representation, surveillance plan view icons, and multiple-screen displays.
- There are no standardized tests currently available to predict an individual's sickness susceptibility to different motion environments.
- There are design criteria that represent fundamental ways that humans best extract information from displays, and there are criteria that achieve their utility by decreasing the amount of time it takes an operator to learn to use a system. It is possible to separate these criteria empirically. Management changes are needed to ensure that contractors approach the design of these displays with a clear understanding of this distinction.
- To determine whether an operator is able to perform a task, when he or she is given a new display/system configuration, task performance issues must be separated from sickness (nauseogenic) issues. Whereas current systems do not apparently yield motion sickness problems that prevent the operator from performing the task, new configurations could well lead to sickness. What is needed is an analysis of existing data bases to determine the relative contributions of visual-vestibular input to display use.
- An important concept in the design of displays/system configurations is *isoperformance.* Isoperformance suggests that the same level of performance can be obtained by different combinations of personnel, training, and equipment.
- Cueing in some form may be useful for different members of an armored vehicle team, depending on whether they are initiating the motion or whether they are simply exposed to the motion. The extent to which an individual is able to anticipate variation in the ride can reduce the likelihood of motion sickness.
- Designers must be made aware that changes in the vestibulo-ocular reflex can occur in training situations as well as in actual vehicle operations. Operators may exhibit what looks like a response to a retrained VOR, including ataxia.
- Successful display design requires a continuous, close interaction between scientists and engineers, who need to exchange information not only about the appropriate display of information, but also regarding personnel selection, safety, and training issues.

Concepts for the Display Interface for Battlefield Commanders

AARON HYMAN

The specific situation the working group was asked to address is illustrative of how displays or display design evolves in a somewhat unstructured environment. The working group was asked to address an early phase in a program in which the operational requirements are not quite crystallized. This gives rise to an iterative process which becomes a learning experience both for the people who are asking for advice and for the experts who are providing it. The material that follows explores various creative possibilities for specific display problems encountered by the U.S. Army in recent years.

COMMANDER'S INDEPENDENT THERMAL VIEWER

Here I describe a project with which I was involved that provided an opportunity for product improvement while a system was being designed by the U.S. Army, specifically, the enhancement of the soldier-machine interface for the Commander's Independent Thermal Viewer (CITV).

Current Army plans call for the development of a CITV for use in tanks. Specifically, the CITV would give the M1 tank commander an independent surveillance and target acquisition capability during conditions of total darkness and degraded battlefield visibility. The idea behind this concept is to make the commander independent of the gunner's sighting system so that the commander can be forewarned of the presence of other targets. Therefore, the commander has the role of conducting surveillance, assessing the environment, and dealing with the total situation outside of the vehicle independently of where the gunner might be directed.

Imagine a situation in which the driver is directed to traverse the terrain in one direction while the gunner is aiming at a specific target with the turret and primary weapon rotated in another direction. Also image that the commander has an independent viewer with 360 degrees of horizontal rotation so that he can gaze anywhere azimuthally. How do you give the

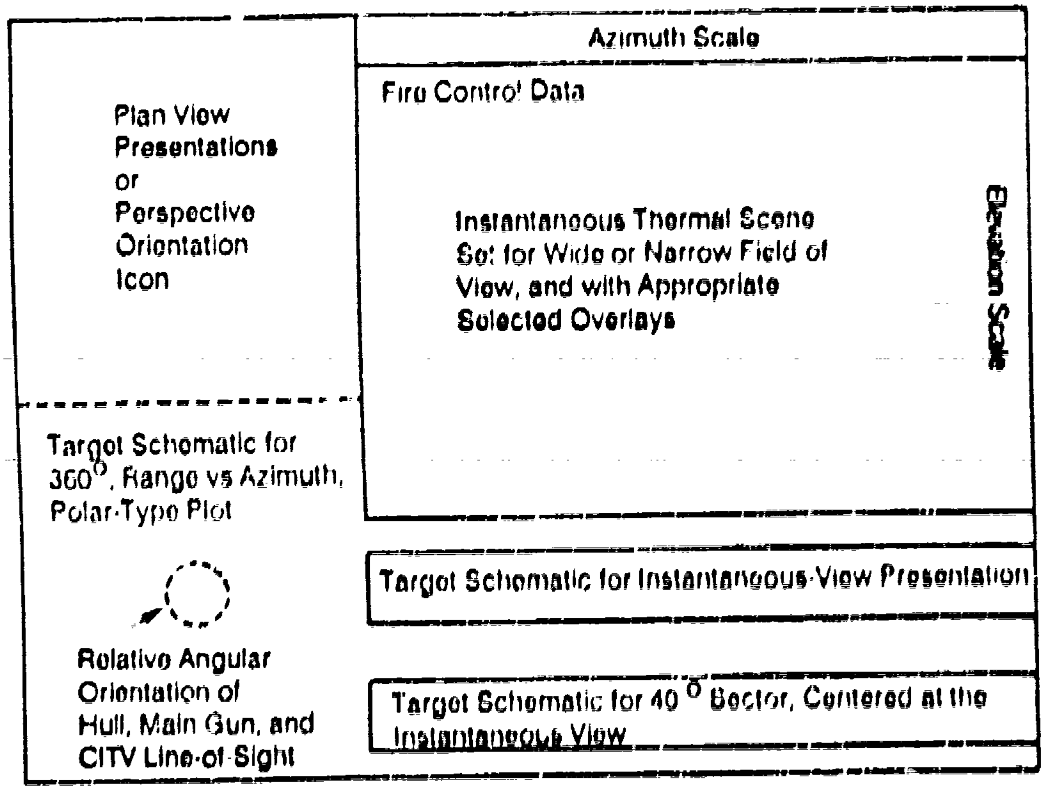

FIGURE 1 Potential location for proposed subdisplays.

commander guidance as to orientation since essentially what he is seeing is being managed by three different operators? What is needed is a system display that would surround the thermal scene with supporting subdisplays in order to reduce demands on the tank commander's short-term memory regarding other crew member activities.

The resolution that is available for the thermal display is poorer than that characteristically available with a 525-line television system. For acceptance, I thought it would be advisable not to come back with a system design that had a requirement for a greater resolution than the commonly available 525-line system. I decided that about two-thirds of the display could be used for the thermal scene (without degradation of its resolution), and the remaining display area would become available for additional information.

In Figure 1, the top right area is the actual thermal display. A sensor that is responsive to the infrared region provides the input that generates a pictorial display. Surrounding this display are areas that can be used to give additional information.

What was being overlooked by the developer was the role of surveillance. It was not being addressed effectively.

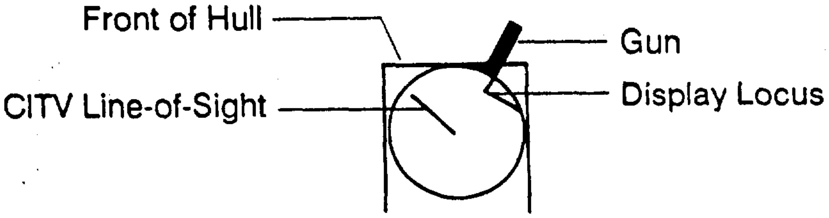

FIGURE 2 Subdisplay for showing vehicle, main weapon, and CITV line-of-sight orientation.

The field of view—when it is large—is about 10 degrees. When it is small, it is about 3 degrees. This is like looking at the world through a tube. It takes at least 3 seconds to assess a display and act on what is seen. If it is assumed that the user is operating with a 10-degree field of view, it takes 18 dwells to scan a 180-degree region without overlap. Multiplying 18 by 3 seconds, it takes about 1 minute to scan the terrain with a 10-degree field of view, and 3 minutes to do so with a 3-degree field of view.

These are not the precise numbers, but they indicate what a heavy demand it is for any crew member under stress. It is a heavy demand even if the crew member is sitting and relaxing. People generally do not realize that such angular fields of view require very long surveillance periods. In battle, a tank may not be able to sit out there and be exposed for 1 or 2 minutes while its operators merely assess the situation visually.

Spatial Orientation Aids for the CITV

In Figure 1, I have defined the areas that can be utilized for augmenting the information of the central display. I will now address the situations that involve orientation. In Figure 2, the information is essentially available symbolically with a plan view of the direction in which the gun is pointed, where the vehicle is headed, and where the commander's independent thermal viewer is directed.

In Figure 3, the icon is also symbolic, but it offers pseudoperspective information, in that one can see the vehicle's direction, the turret gun direction, and the direction of the independent thermal viewer as well as its elevation from an oblique view. The success of this symbolic representation has not yet been tested. The advice that was given to Fort Knox on this project was that these concepts should be field tested before implementation.

Figure 3 also provides five different orientations. Orientation reference can occur through computer selection so the icon can represent track up, north up, turret up, or commander's thermal viewer up. Therefore,

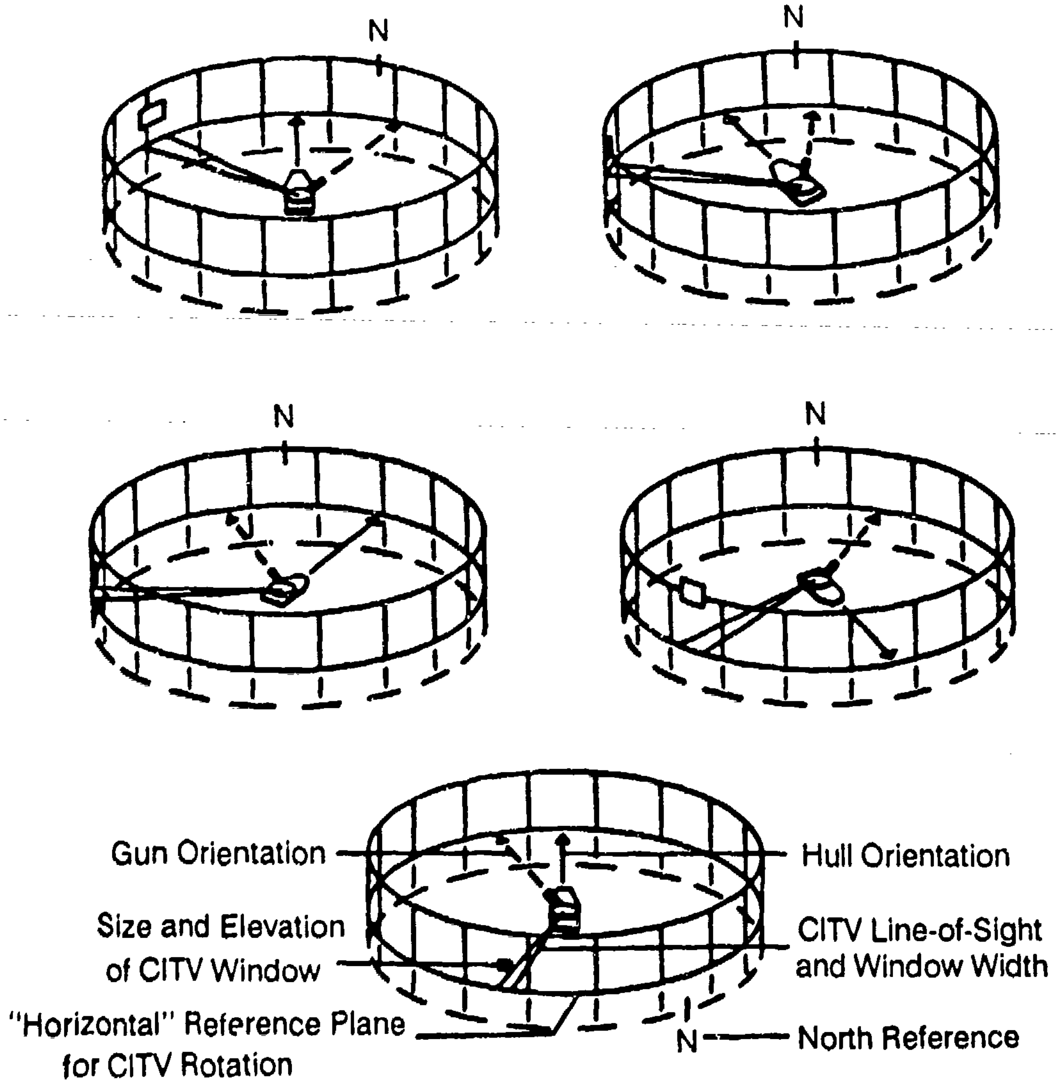

FIGURE 3 Several orientation icons presented in perspective view.

the user can have different references from which he can make angular measurements. The lowest panel in Figure 3, for example, indicates a hull-up type of display.

In stressful situations, information may need to be redundant, in which case a simple display is needed with only the essential information presented. This type of display is illustrated in Figure 4. People working in a stressful environment probably have an advantage if the same information is repeated in a different format. The phrase I use for this is *cognitive coherence*. This is a design concept or principle of aiding one's grasp of a total situation by presenting two or more related information subdisplays in a manner so that they logically and partially redundantly reinforce each

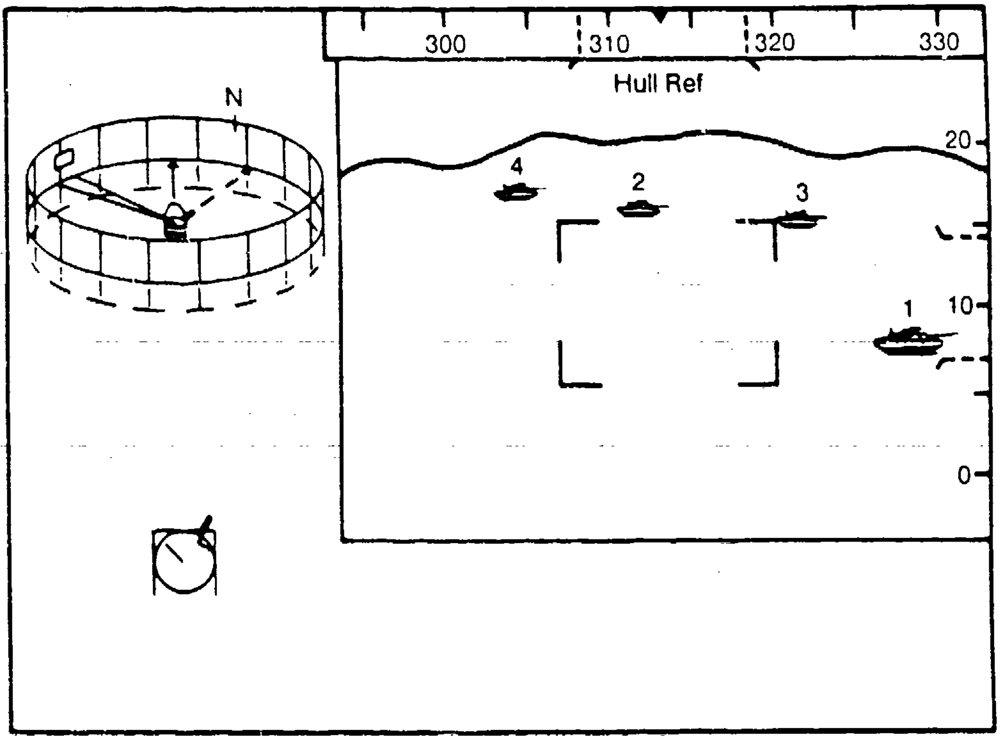

FIGURE 4 Orientation subdisplays.

other. In the upper left of Figure 4 is an icon showing the perspective view of orientation; in the lower left is the classical icon in plan view; and in the upper right is a tapelike azimuth scale. These were three orientation suggestions to be evaluated by Fort Knox either individually or together. The two icons on the left cannot give finely resolved angular information. On the other hand, very often that kind of precise orientation information is not needed, in which case the icons on the left are adequate and the detail of the azimuth scale is not needed.

Notice that the azimuth scale only covers the field of view presented by the display itself. When the display is a 10-degree view, that is all that will be seen in the azimuth tape window; and when the display is a 3-degree view, that is all that will be seen in the azimuth tape window. Note that the azimuth readout is an identifier with reference to whatever is considered up. In this case, the hull reference was used, but it could have been set for north reference.

Surveillance Aids for the CITV

Surveillance is another domain in which what we wish to provide to the commander is a gross summarization of what he has already seen. The

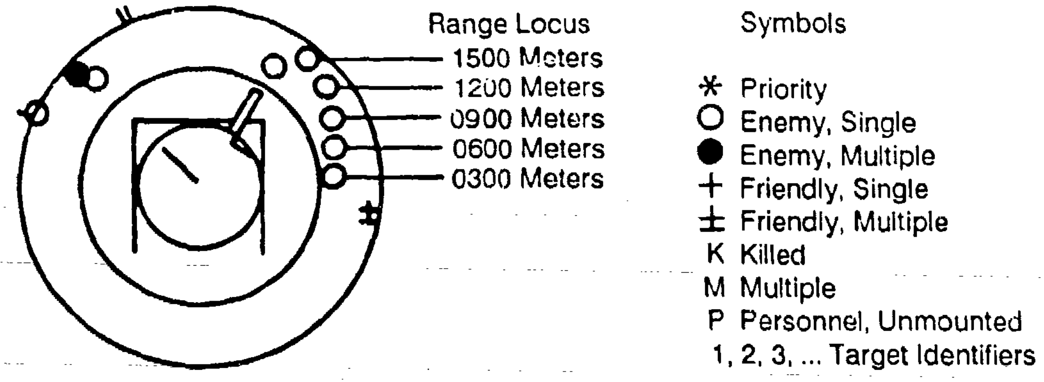

FIGURE 5 Location of entered targets displayed in modified (i.e., annular) plan view.

assumption is that when he sees areas of interest, he can define by specific symbols those things representing primarily the enemy targets; but he might want to include the "friendlies" as well, so that he does not shoot at them.

Figure 5 shows one such design, in which there is a distortion of distance, so that the region from 300 meters to about 1,500 meters out is represented by an annular ring. The icon placed in the center is a plan view icon designed to give the commander correct orientation information regarding the azimuthal reference. In terms of range, however, the annulus introduces a spatial distortion in range, for it goes from 300 meters to 1,500 meters—but that may be all he needs to give him an understanding of the situation.

Because of resolution limitations, the symbols that define a target may be much larger than the target itself, so there is a problem of overlap with high-density targets. One solution is to represent units themselves rather than specific targets—such as a platoon rather than single tanks.

Another novel concept is to magnify a 40-degree section of the surveillance icon so the commander has access to critical annular information (see Figure 6). This, of course, introduces azimuthal distortion in the magnified presentation. As previously stated, the inner ring of the annulus represents a selected near-reference range and the outer ring represents a more distant reference range. The tick marks on the magnified sector identify the existing field of view, with the clockwise edge having a double mark, because orientation can be rearward. This display might be confusing or it might be helpful. Again, it should be evaluated in the field.

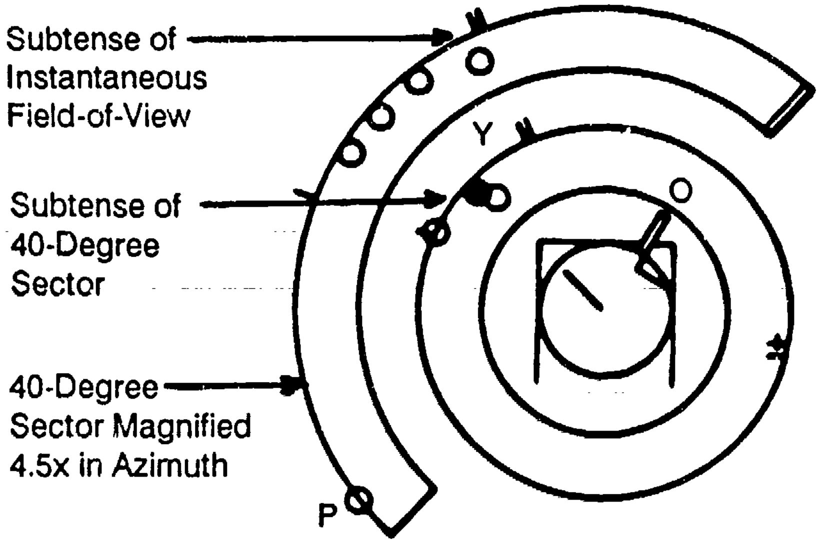

FIGURE 6 **Magnification of a 40-degree sector for better location resolution of targets shown in the annulus.**

Field Evaluation

Let me point out that it is characteristic of field evaluation that subjects who are familiar with a particular system may have a problem with a modification of this system. What is needed is a qualified observer class that is naive with regard to the "old world." It took years for the Air Force to change their aircraft panel instruments because of the preference by pilots for the old versions. Even though human factors evaluation pointed out that the redesigns were superior, the previously trained pilots did not think so. For them, the new designs were truly not good because of negative transfer from the old ones. For a new system to be evaluated fairly, it should also be tested by people who are not familiar with the old system.

Figure 7 includes another kind of symbolic surveillance presentation. The world scene can be found in the upper right region. The two horizontal bars below it schematically represent azimuth versus range plots for the detected targets. The upper bar has the identical azimuthal subtense as the thermal scene. The lower bar presents a fixed 40-degree sector centered on the thermal scene. The commander thus ends up seeing an overview of an evaluated situation (lower bar) as well as its expansion to the immediately displayed area (upper bar). These horizontal bars also correlate with the sectors on the left. This is an example of what I mean by *cognitive coherence.*

In Figure 8, the concepts I discussed earlier are presented in all their confusing complexities. I made the assumption that field testing would

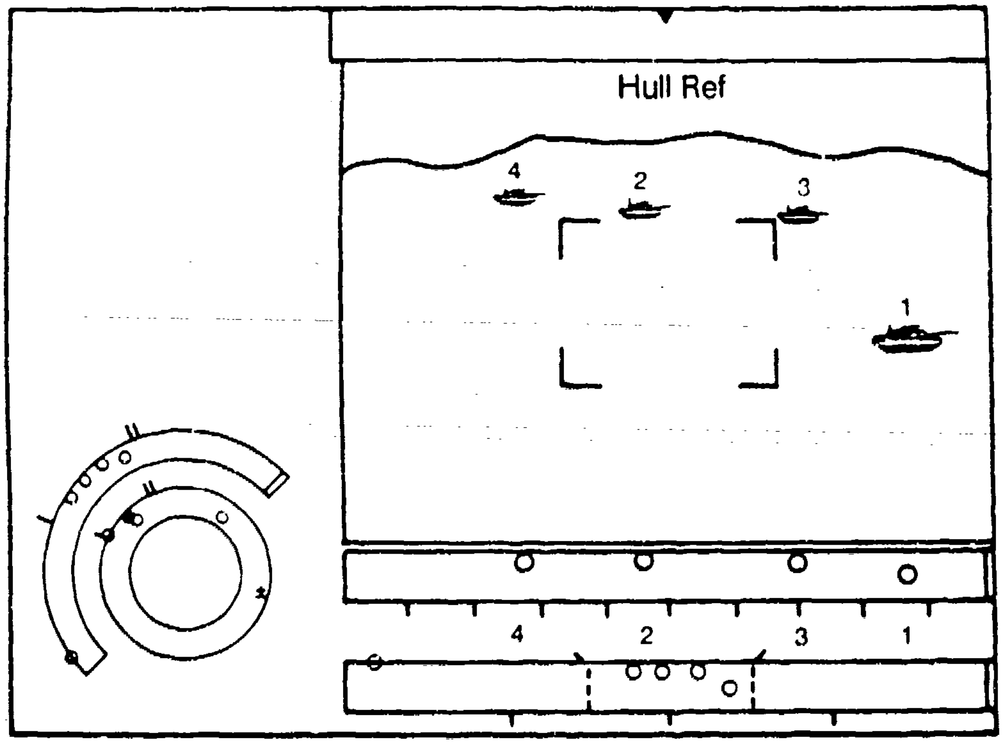

FIGURE 7 Surveillance subdisplays.

help eliminate the unneeded redundant aspects of the displays. Should field evaluation indicate that less redundancy is needed, reduced clutter in the symbolic subdisplays could be achieved, as shown in the lower half of Figure 8.

HOW LARGE A DISPLAY?

The amount of information a commander needs must be much greater than that being offered by the various designers of military display interfaces. One constraint has been that designers characteristically come up with displays that subtend about 20 degrees of visual angle to the observer.

A workable extensive display would consist of existing state-of-the-art technology, namely, 17 1-inch cathode ray tubes (CRTs) and accompanying optics, that can be put together in about 1 cubic foot of space. The display can be viewed through an eyepiece configuration with about 3 inches of eye relief. The design is based on the concept that involves essentially three display subsystems with three contiguous eye lenses, and with subsystem viewing directions set so the display would be viewed with both eye rotation and neck rotation to reduce stress on the extraocular muscles. Figure 9 shows a schematic optical layout for one display subsystem. Not shown

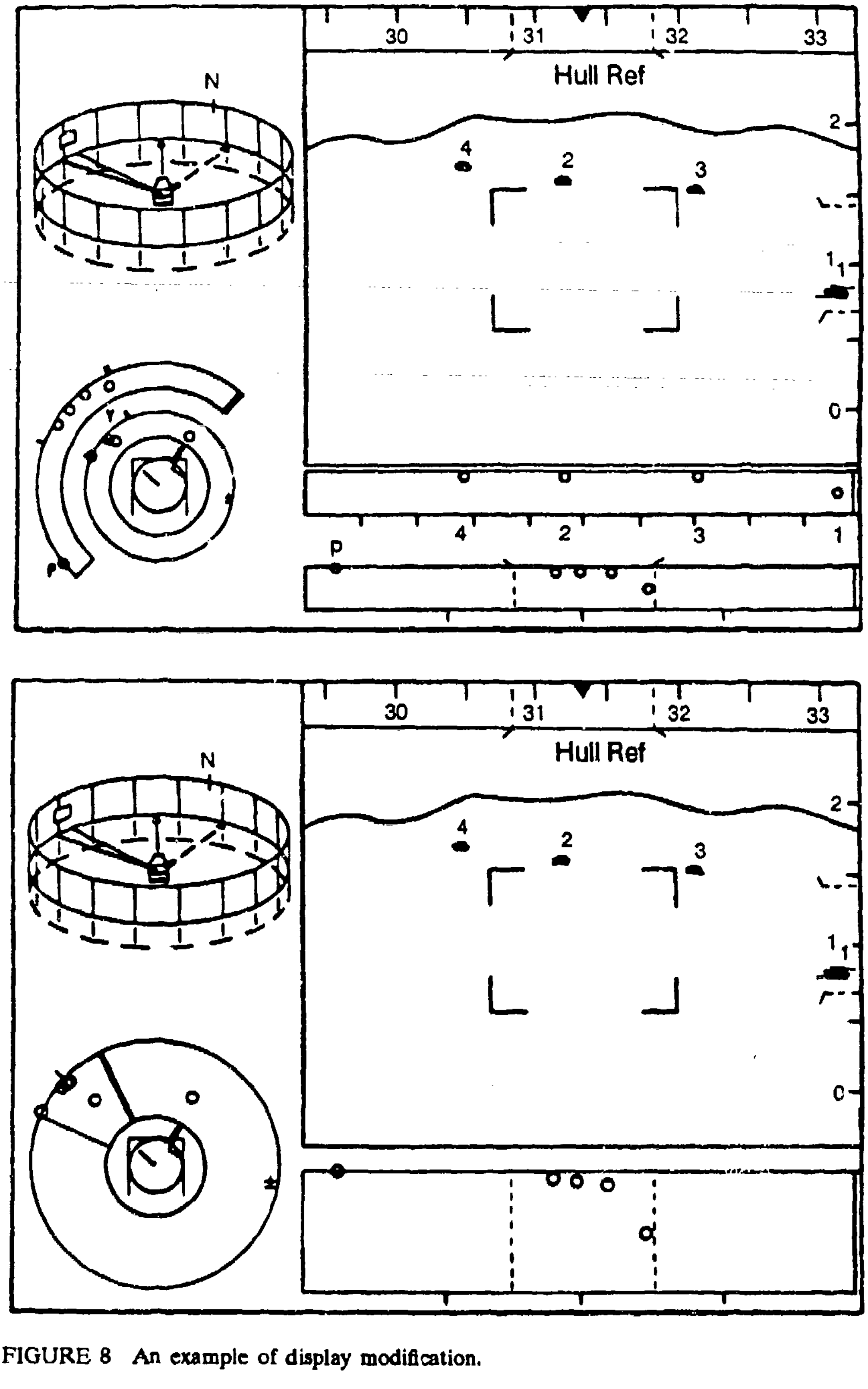

FIGURE 8 An example of display modification.

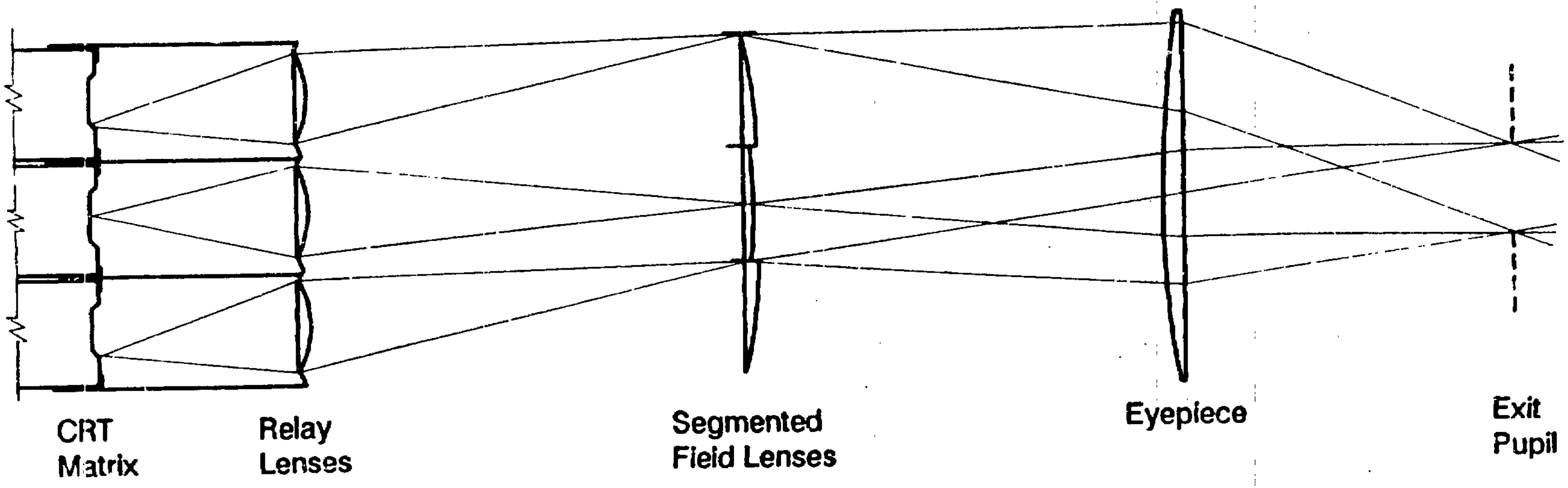

FIGURE 9 Schematic of the lens system for one section of the multiple-screen display.

is the associated placement of the exit pupils for the two other display subsystems. For total viewing, eye position depends as much on head rotation as it does on eye rotation, and this impacts on the exit pupil location for each subsystem.

I have not examined the literature or studied the question in detail, but empirically I have found that if you ask people to rotate their eyes by more than about 10 degrees, they are likely to include a neck rotation even when the viewing system does not require it. This is an aspect that should be considered when using helmet-mounted displays or anything that is fixed to the head. If you have to utilize an extended field of view, you can only see the lateral parts of this field of view with relatively extreme eye rotation, and that may not be a very comfortable way for viewing displays during military operations.

As far as the proposed extensive display is concerned, if each CRT had 500 or 600 pixels of horizontal resolution, this configuration would yield a presentation with about 2,400 pixels laterally and roughly three-quarters of that vertically. It is possible, of course, to include additional subsystems with contiguous exit pupils. The problem then is that the nose may get in the way. Incidentally, this system has been designed for one-eyed viewing and has been made so that one could view the total display with either the left or the right eye. This eliminates concern about discomfort with binocular viewing, in which even small differences in distortion are a major problem.

This system has actually been mocked up and it does work. I used inexpensive ophthalmic lenses as eye lens elements, so it failed to exceed the required resolution; but I think with good optical design, you could actually make the optical system resolution better than the resolution provided by the stimulus inputs. The main purpose of this exercise, however, was not just to come up with a dense display. I was concerned about the information that a commander needed to control his organization in a battle situation. Such an extensive display would likely be used by the commander of a division or a corps.

In what I call the *stored imagery* display, information could be on board the vehicle or stored centrally and telemetered to it. In this case, I assumed that satellite imagery that had been stored on a previous occasion would be presented, when needed, in order to provide historical information of the geographic area. Tactical operations information is displayed below the stored imagery display section. Starting in the upper left and going counterclockwise, the first tactical subdisplay shows the general area the commander is involved with; the next one shows the specific area of responsibility (with greater detail). Both of these are maplike plan views with whatever overlays are needed. Below the detailed tactical presentation is alpha-numeric status information, and to its left are the command orders that the commander has received or has transmitted.

The real-time display deals with the cognitive correlation among multisensor inputs. The first is a stored image of the general area. The next one is a selected zoomed image, and the region that is zoomed is indicated in the stored imagery display area by a rectangular reticle. Correlated infrared information and correlated radar information are also presented. However, these need not be rectified, for the human being is capable of cognitively integrating several subdisplays that are not totally isomorphic with each other. The operator is perfectly able to look at frontal displays, plan view displays, zoomed displays, and minified displays and still come up with a cognitive appreciation of what is out there without having the machine organize everything first.

Final display design is governed by a number of system considerations and requirements.

DISCUSSION

DR. HELD: Why is the exit pupil a consideration?

DR. HYMAN: The eye must be positioned to intercept these exit pupils. The angular subtense of the display is what matters, not just its physical size. You bring your eye in to the lens system. You arrange it so viewing is comfortable and natural to the observer.

As represented in Figure 9, one way to build such a display interface at the present time is to use matrices of 1-inch CRTs. These CRTs can each provide a rectangular image of 0.60 by 0.45 inch (for a three- by four-aspect ratio). A relay lens can then expand each image to 1.33 by 1.00 inch, and with appropriate mounting and baffling, contiguous images can be obtained for the units comprising a given matrix. A segmented field lens placed in the image plane would then direct the light rays through the eyepiece to form a common exit pupil region for all CRT displays comprising that matrix. Eye relief can be designed to be 3 inches. The separate sections, each comprised of a matrix of CRTs, could be mounted so their eyepieces were contiguous and their exit pupils appropriately located. If color displays were desired, a field-sequential color system could be employed, utilizing the liquid crystal shutter technology. A three-section display as described, and using folded optics, could be designed to occupy less than 1 cubic foot of volume. Hence, such a display could be mounted in a tank or even on a jeep. The upcoming technology in miniaturized, high-resolution, flat-color displays should permit an even simpler interface for multiple-screen displays in the future, particularly if screen resolution is great enough to permit windowing in each display subsystem presentation.

DR. EBENHOLTZ: Are there distance requirements?

DR. HYMAN : Yes, there are eye-positioning requirements. These are collimated displays. Viewing is monocular.

DR. HELD: So, if I understand this, you see those displays essentially one at a time. Is that correct? When you look at this display, you can only see, at one instant, the subtense given to you by one of those eye lenses. Is that correct?

DR. HYMAN: Without eye and/or neck rotation, you can only see one of these subsystems.

DR. HELD: Yes, and one of those subtends how many degrees?

DR. HYMAN: Forty degrees.

DR. HELD: Forty degrees. So the total is 80 degrees because you have two lenses.

DR. HYMAN: Right. You could make it 120 degrees by having three lenses.

DR. HELD: Beyond that 40 degrees, I would see a luminous aperture, is that right?

DR. HYMAN: You would probably see nothing if no light gets into the eye. It is a function of how you have designed exit pupil locations so the rotation of the eye intercepts the light output.

DR. HELD: For some purposes, you might want that peripheral information.

DR. HYMAN: This is a cognitive display. This is not for detecting targets in the periphery or responding to movements.

DR. WALBERT: Would you explain again the difference between the stored imagery display and the real-time display?

DR. HYMAN: Real time involves sensors in the battlefield. Stored imagery is information collected by intelligence. It could be through satellite or stored from a previous overflight.

DR. WALBERT: As the tank is in motion, the upper left third will be static or fixed. Is that correct?

DR. HYMAN: It would be a selective option. You could call up any kind of intelligence. I have just made the assumption that this is a satellite overflight. It need not be a satellite overflight.

DR. WALBERT: But the others will change in time.

DR. HYMAN: The display changes continuously. There is the real-time one, based on battlefield sensors. And there is a standard tactical display. It has maps, battlefield overlays, status reports of what troops are ready, command information, etc. Essentially, the lower left region is reserved for presentation of the battlefield tactical display that the BRL [Ballistics Research Laboratory] is concerned about, and the upper left region is for stored intelligence information coming from any source. It could have been obtained from an earlier overflight of a reconnaissance aircraft.

DR. VAN COTT: Would the scale of the stored imagery display be such that you could enrich what your cognitive knowledge was of the real-time display?

DR. HYMAN: That would depend on how you plan things. The trouble with electronic collection of information is that you cannot zoom and necessarily get increased resolution. In other words, in attempting magnification you are limited by the resolution at which the system was set for obtaining the original data.

DR. HELD: Maybe I am asking the same question, but what are the objections to having a real-time display use this system?

DR. HYMAN: The real-time display is using this system. The one comprised of this matrix of four CRTs and sitting above it is the matrix of nine overflight scenes.

DR. HELD: So how do you get to the matrix of nine? You raise your head?

DR. HYMAN: Yes. Actually, what you do, to see the lower ones, is to lower your head because raising your head by a large amount is uncomfortable. So essentially, viewing straight ahead is the raised head postion. So I should say you lower your head for viewing the lower regions and you look vertically straight ahead for viewing the matrix of nine.

DR. BLAKE: If a commander is bumping along in a multiunit vehicle, how critical is this motion to the optics?

DR. HYMAN: If you want eyepiece viewing and you are vibrating, it is a problem. You may have to stop to look at the display when high-resolution viewing is needed. On the distributed battlefield, the commander may be in an armored vehicle; but when that vehicle stops, it need not stay long enough to be picked out as the primary target to be destroyed. If you now have a vice commander in a redundant command post, you no longer have the vice commander next to the commander, but as a plus if one command post is destroyed, both are not destroyed.

DR. KENNEDY: Can stability problems be overcome with the helmet-mounted display?

DR. HYMAN: In a helmet-mounted display, you could have a 20-degree field of view and still see 180 degrees of azimuth by rotating your neck; however, the sensor has to rotate in a correlated way. In such a case, you could not make as easily those short-term memory comparisons that are allowed with the extensive fixed display.

DR. KENNEDY: What is the practical limit to the number of lines of information in the display?

DR. HYMAN: This is a problem. It is feasible to have 4,000 pixels with the current state of the art. How you decide to utilize the 4,000 pixels is a decision that the designer has to make. Note that the subtense of the instantaneous, high-resolution viewing area available with the eye is very small—less than 1 degree—so eye scanning is required.

CONCLUSION

A very important step in the design process is uncovering the problems. This is a contribution that can best be made by a working group such as this one. The scientist learns to think of things in terms of user needs, and the user tends to think of things in terms of the information developed by the scientist. The real goal, however, is to resolve the problems rather than only to become aware of them. Problem resolution requires more of a continuous, close interaction among all design team members. I am not talking about meeting once a month, but rather with a very high frequency. These should be meetings in which members of each discipline learn what those in the other disciplines know, and they all become familiar and semiexpert in the total area. I have used behavioral and social sciences as a rubric to cover all of the situations. The Army has developed another term for it. They call it MANPRINT. To design a system, you have to deal with the manpower available, personnel problems, training problems, human factors problems, safety problems, and hazard problems, as well as engineering and equipment development problems.

I strongly suggest that some means be evolved to promote this close interaction between the scientists and the ultimate users. The ultimate users might be the Ballistics Research Laboratory or they might be the people at the U.S. Tank and Automotive Command. The Army must be made to understand that their decisions have an impact on the design of a system in an iterative way, with constant interaction among scientists, developers, and users.

Oculomotor Factors and Design Requirements

SHELDON EBENHOLTZ

I would like to review the interface between oculomotor factors and the design requirements for visual displays. *Asthenopia* is a term used by optometrists to refer to many eyestrain-type problems that emerge from accommodation, attempts to accommodate, attempts to verge, or attempts on the part of other oculomotor systems to align themselves. There are numerous conditions under which one comes to experience what is known roughly as eyestrain. I will try to identify some regions, some areas having to do with visual displays, that are likely to lead to these problems and to suggest a theoretical approach to these problems.

The reason for dealing with asthenopia in the context of this project is that it leads to discomfort. It is a sign of a dysfunctional state. Some of the indications of asthenopia feed into a pattern that we now recognize as belonging with motion sickness. Asthenopia can merely be a headache; it can be a feeling of nasal stuffiness; it is sometimes associated with a feeling of dryness in the eyes. It also produces more vegetative-type symptoms, so it can produce stomach upset, vomiting, and so on. At some point, it mimics very closely the signs and symptoms of motion sickness in general.

OCULOMOTOR CONTROL

The issue that I want to begin with concerns a theoretical approach to problems associated with oculomotor function that can serve as a basis for understanding how dysfunction can occur as a result of changes in oculomotor function (Ebenholtz, 1986). Figure 1 illustrates the control system associated with convergence and accommodation. I want to use it here as an example of how it is that we might go from an adaptive state on the one hand into a dysfunctional state on the other. The characteristics of adaptation are represented in the little feed-forward loop through the tonus controller. It is sometimes called the slow controller. The outer loop

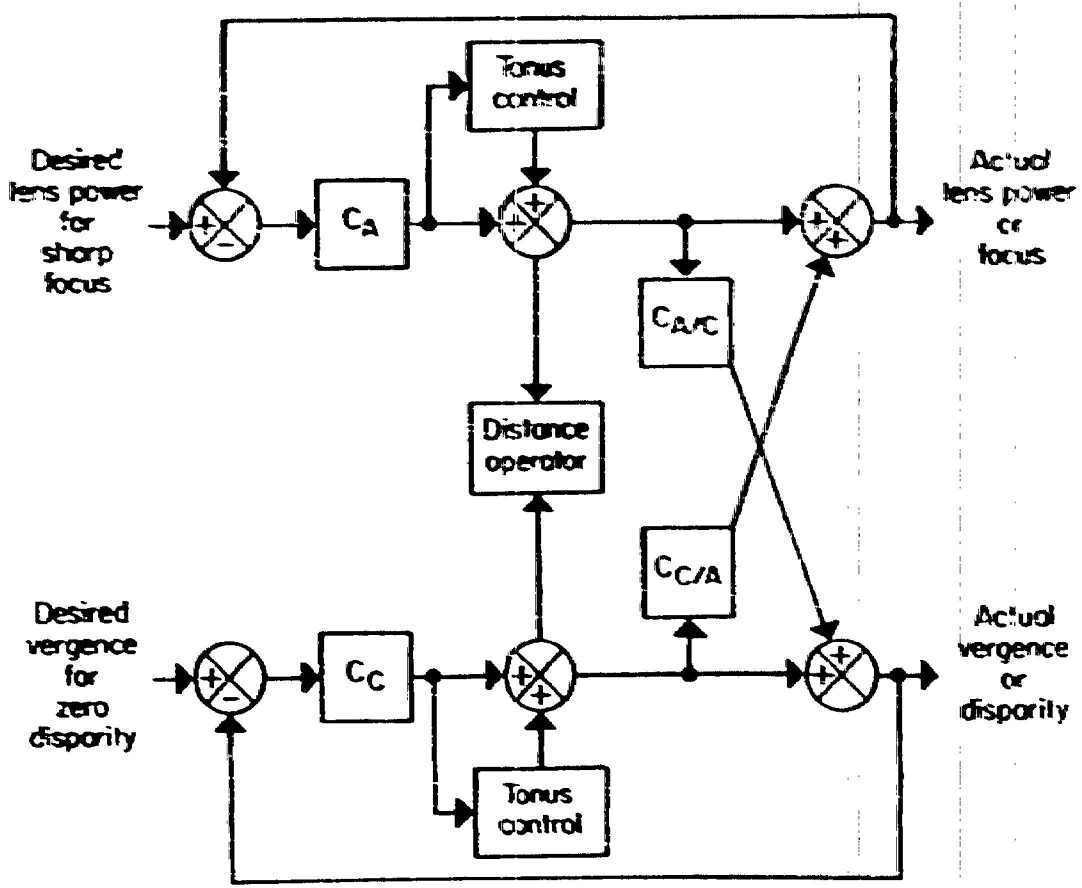

FIGURE 1 The oculomotor control system. C_A = accommodation center; $C_{A/C}$ = accommodation and convergence controller; C_C = convergence controller.

is a simple feedback control system. There is an attempt to focus, followed by a comparison with a criterion for proper focus. If there is a difference in the system, the system moves in the direction of eliminating the difference and it sends through an error-correcting signal. At this point, if that is all there is to the loop, it is just a typical feedback loop. There are, however, what have come to be called the fast-acting or fast-integrating systems. Feedback takes place within the normal latencies of the system—in this case, in under 500 milliseconds.

The purpose of that signal is to eliminate the errors that it has been sampling. It looks at it over a reasonably short period of time (our research has shown that this adaptive loop begins to kick in after about 2 to 3 minutes of constant focusing). Before that time, you get what looks like a transient effect that then dies out within seconds. After this time, the tonus control mechanism (the adaptive part of the loop) serves the function of turning up the tonus in the ciliary muscle to change the focusing mechanism. It does this with a feed-forward signal.

The net result of all of this is to wipe out steady-state areas in the system. If you are focusing at a target and you measure the accommodation, it turns out that you are not quite accommodated for the target. This is called accommodative lag. If you maintain focus for a short period of time, you find that that accommodative lag is gradually reduced to near zero. That is the adaptive aspect of the system.

This is a plastic system, so that not only is it adaptive while the demands are being made, but, if you take away all stimulation (remove the target on which you are accommodating), you find that the adaptive system continues to operate. In fact, it continues to control the ciliary muscle and hence the lens focus in the direction of the near point, assuming you were focusing at near-point targets. It looks as though the system adjusts the ciliary muscle so that it would be effective if the target were where it initially was, even though the target no longer is there. We take this to be an indication of plasticity because it is as though the system has a memory and retains its signal until the system is reset, and you reset it by making another demand.

The essence of the system is that there must be an error signal coming across the system. There must be an error signal, and the system must then act to correct those errors by adjusting system parameters so that future errors become less likely. That is the essential requirement for these adaptive control systems.

NEGATIVE ASPECTS

The negative side of this adaptive feedback system becomes evident when we attempt to induce adaptations in various oculomotor systems. We find that the very same stimulus conditions that lead to an adaptive response also lead to some of these dysfunctional states of the system. If, for some reason, you cannot adapt rapidly enough, you wind up showing signs of dysfunction. You begin to report eyestrain or vegetative symptoms; you are on your way to a dysfunctional state. Thus, the very same stimulus conditions that trigger adaptive states will, if you keep the subject in this situation long enough, lead to eyestrain symptoms and so on.

What kinds of situations might trigger this state of affairs? To illustrate this, I would like to turn to a different control system, but the essentials are the same as those in the adaptive feedback system. The system in Figure 2 is intended to represent a possible way in which the vestibulo-ocular response (VOR) could be understood in the same way as it is in the case of the accommodative system—that is, as being adaptive and representing plasticity. The VOR is a very functional response: If you are exposed to some inertial stimulus, such as an acceleration great enough to trigger the semicircular canals, then you will get a corresponding output in the oculomotor system.

The purpose of this functional aspect of the output is to eliminate displacement so that the eyes will remain at the same stationary place in space, even though the head may have moved. Gaze stability, then, is regarded as the primary function of the vestibulo-ocular response. Imagine being able to keep your eyes straight ahead while moving your head around your eyeballs. You can accomplish this because of the vestibulo-ocular response. It operates very rapidly because it is a feed-forward system, it is adaptive, and it exhibits plasticity.

We have many data to show that we can alter the gain and phase of the VOR. So, instead of having a velocity and an eye direction that is opposite the head movement, we can now create virtually any kind of eye-head relationship given suitable circumstances. It is very easy to adapt the VOR.

Sources of information that help to adapt that response are believed to come from the pursuit system or the optokinetic system. In other words, you educate the VOR by examining the velocity of patterns across the retina. If that velocity pattern is different from the VOR as it normally operates, then the VOR will adapt itself to follow the new velocity requirements. If you are looking at a target while moving your head, for example, and if that target then moves correspondingly, then the VOR will come to reflect

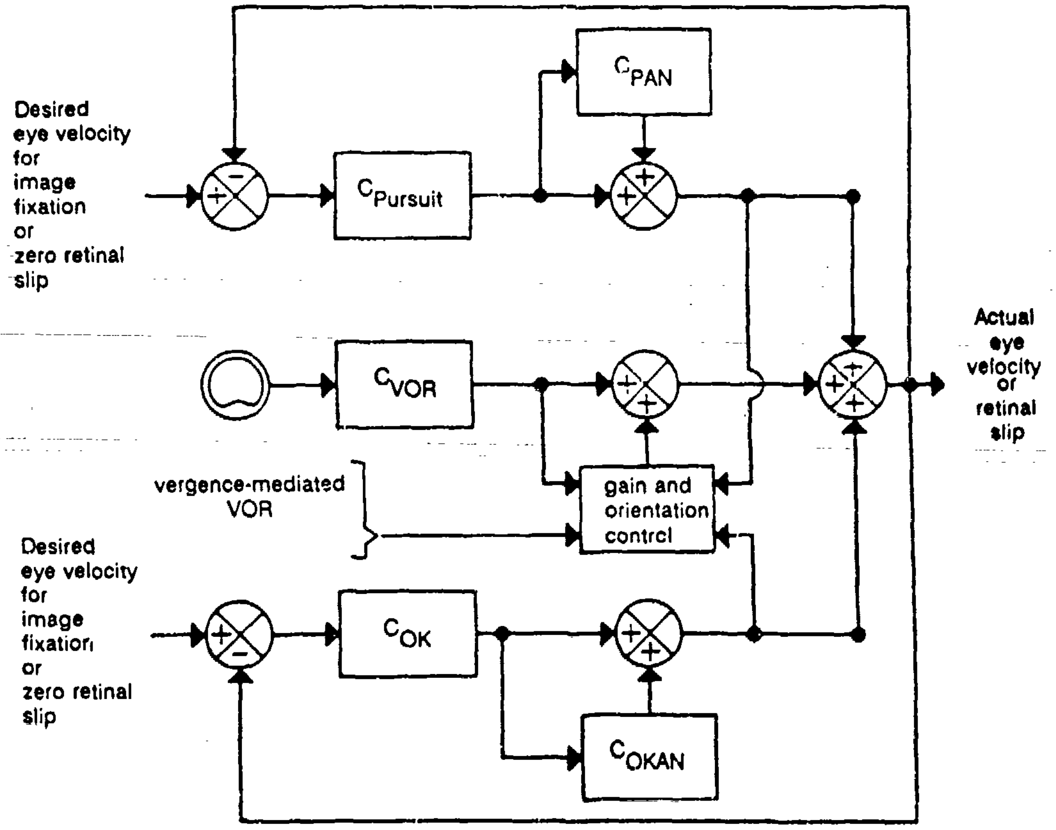

FIGURE 2 Vestibulo-ocular optokinetic system. C = controller; PAN = pursuit after nystagmus; OKAN = optokinetic after nystagmus; VOR = vestibulo-ocular reflex. Gain and orientation controller represent the presumed source of adaptive plasticity. Source: Ebenholtz (1986).

the velocities that are present in that situation in order to achieve a new level of gaze stability.

If you happen to be looking at a display in a bumping, moving vehicle such as a tank, then it seems you must begin to consider what you are going to do to the VOR. Suppose you are looking at a display that is receiving the same kind of inertial stimulation as your head: if the head moves up, the display moves up. That conjunction serves to defeat the vestibulo-ocular response because the eye movement signal that occurs when the head goes up moves down in order to enable you to retain gaze stability. That is precisely where the display will no longer be because it has moved up as well. Consequently, if you maintain fixation on the display, you put the observer in a condition that is meant to produce adaptation of the VOR. Depending on the variety of stimulations that occur, you may get a series of adaptations in different directions, or you may just get a series of error signals. That is what disturbs me about the possibility of having to view displays for long periods of time in moving vehicles. It seems to me that there is a certain probability that this will lead to dysfunctional consequences.

One possibility is to build a device so as to stabilize displays, much like those found on a naval platform. In that situation, you would stabilize the target so that if the tank moves up, the display will move down. In that way, your VOR will again be functional for that display.

DR. LEIBOWITZ: Why can't you just adapt to the new condition?

DR. EBENHOLTZ: I think you would adapt if you took a spectral analysis of the distribution of inertial forces and if you had enough energy and error signals in the same direction. I'm assuming, however, that it is random and that, consequently, you are not going to have the benefit of that.

DR. HYMAN: If the display were collimated, what effect would that have?

DR. EBENHOLTZ: I have some special problems with collimated displays that have to do with other control systems, namely, the accommodation and the convergence control systems. If you use a typical infinity optics display—and I say typical because they seem to be very popular—if the optics are correct, you have a condition in which accommodation is required to be set for zero diopters.

In the old physiology and optometry textbooks, you used to see statements to the effect that optical infinity was appropriate because that is where the eye rests. But ever since Herschel Leibowitz and his colleagues explored that assumption, we know that individuals have a resting level of accommodation that for most people is at some intermediate level between optical infinity and their near point. Consequently, you are asking most people to do work by looking at a collimated display. If you have them maintain a sharp focus—that is, if their accommodation system is going to meet the demands of the light rays placed upon them for clear vision—then they are going to have to do work continually.

What does that mean? For many people it means that you are putting them in a conflict situation, because there are problems with maintaining relaxation of the ciliary muscle, when, in fact, the system has to be under power continually. That is, the system must actively inhibit, through the autonomic system, sympathetic loops in order to maintain this condition.

There is a relationship between accommodation and convergence, and in those systems that only use monocular vision, you may be buying something that is good. That is, you may be buying your way out of a problem having to do with a conflict between accommodation and convergence of the eyes. Most individuals have their vergence system rest at a different position from their accommodation system. We call that heterophoria. So if you are accommodating at a certain distance and measure the free state of the vergence system at the same time, it turns out that for objects that are near, your eyes are too far apart. They are deviating in the exo-direction so that they have to do work to point toward the same object. For some individuals, they have a heterophoria at the far end. You do not know this unless you examine them. For individuals that have a heterophoria at the far end, it means that not only does the accommodation system have to work in order to be in this so-called relaxed position, but the heterophoria guarantees that the convergence system must also work to put the eyes in a relatively parallel position. So you risk engaging individuals in a situation in which work is required continually over a long period of time, and if it is intense work, one may add even more to this problem because of the potential role of stress as a factor in oculomotor function.

There is another unfortunate aspect of optical infinity displays, and that has to do with the nature of lens and mirror aberrations. I find it to be a very complicated domain. Not only do you have spherical aberration coma and astigmatism, which in their various manifestations wind up producing defocused signals, but you also have chromatic aberration in nonmirror displays that use normal lens optics. Fortunately, in mirror displays you do not have to deal with that, but if you introduce color into these displays, you are going to add to this problem because of the presence of frequency-dependent aberration.

The nature of the problem from the point of view of dysfunction is simply that images will not be as clear as they should be. You are going to make demands on the optical system from a human factors point of view that for many of these aberrations simply cannot be satisfied properly. The net consequence, therefore, will be that there is an error signal that simply cannot be eliminated. Given that general approach, a red flag should go up. If you have a choice, then, one should think very carefully about using infinity optics. If, however, these systems are used, great care should be taken to properly calibrate and position each element of the system.

There may be some fixes, but I think they are expensive. I know there are some fixes for some of the problems of spherical aberration, including lens bending. But we are talking about putting these things in tanks, where vibration is going to be a problem, so I doubt that the normal fixes are going to be applicable for aberrations that occur in tank systems.

I have a story about individuals who no longer have VOR: there is no substitute for data as such, but the fact is that if you have an eighth nerve section, so that you no longer have an operating vestibulo-ocular response, it is very difficult to walk. That is, a person who attempts to walk will find out that he is carrying his eye at the same amplitude and velocity as his head, which is enough to cause severe motion sickness. Such individuals cannot read unless they stabilize their head. This indicates the sensitivity of the VOR.

I have one or two other comments about other types of adaptation. There is a type of reflex that I have called the "doll reflex" based on the kind of doll that has eyelids and a movable sphere for an eye so that if you tipped the doll back, the lid and the eyeball would move downward. In fact, humans also have such a reflex. It is believed to be an otolith-driven reflex. If you tip your head back, then the resting level that you would normally find with respect to the straight-ahead position of the eye deviates downward. This has been documented quite well. It is analogous to the torsional response that occurs with sideways tilt, but this occurs in the pitch direction.

If we have individuals tip back and they are asked to elevate their eyes and to read or extract information, we know that maintaining this task will adapt the straight-ahead position of the eye. Those individuals who then look at a target mislocalize that target in elevation.

This has been explored in connection with baseball players (Shebilske, 1986). Shebilske adapted two sets of baseball players, one of which looked up, the other of which looked down. Then he predicted which set was going to hit pop-ups and which set was going to hit grounders; the predictions worked very well.

DR. KENNEDY: How long does it take to induce that response?

DR. EBENHOLTZ: Approximately 6 to 8 minutes. These are relatively rapid induction procedures.

DR. FLATTAU: Would placing a finger on a display screen correct the mislocalization of a target?

DR. EBENHOLTZ: If the finger is in the field of view, then you can bring the finger into coincidence with whatever you are looking at. But, if you are looking at a target and there is nothing else to help you to sight, you are going to get a misestimate of its elevation.

DR. LACKNER: Would a cursor obviate the problem?

Dr. EBENHOLTZ: Yes, a cursor may obviate the problem.

There are just one or two other areas that I want to cover. One has to do with sideways or version movements. Those, too, adapt. The same caution, however, must be observed.

Ever since psychologists started putting displacing prisms on subjects, it has been known that you get aftereffects as a result of having moved your eyes more or less in the direction of the apex of the prism. You can also get effects without a prism merely by maintaining a skewed posture. An asymmetric posture will induce aftereffects, and those aftereffects will occur both in the version system that controls the joint parallel movements of the eyes and also in the vergence system that controls the oppositely moving of disjunctive directions of the eyes. This leads me to the final point.

If we are talking about living in a near environment for a long period of time, perhaps 5 or 6 hours at a time, then it is conceivable that some of the literature on those in submarines may be appropriate. We have some good studies from JoAnn Kinney and her colleagues from the U.S. Naval Base at Groton (Connecticut) that show vision changes in individuals who have lived in a close environment (a submarine) over several months (Kinney et al., 1974, 1979, 1980). I would begin to look at these people for possible long-term, permanent changes in accommodation and convergence. There is a need, then, for data collection as people are put into some of the other situations that are similar to those in submarines.

DR. LACKNER: Do you find any evidence for specificity of the VOR to a given situation?

DR. EBENHOLTZ: Yes, the VOR has enormous specificity. You can adapt in the horizontal but be completely unadapted in the vertical VOR. It is absolutely remarkable to see a person exhibit change in gain of the VOR in one direction but not in another. So you have the possibility of enormous specificity in the adaptive capability of the person. But that does not answer the tantalizing question about whether there is something like a switch where you can actually turn it on and off. Dr. Kennedy, have you seen evidence for it?

DR. KENNEDY: No. All the measures we are talking about are of the sort: If I adapt to A, do I also have adaptation to B? I don't know if there are any good data of the sort: If I adapt to A, is the time it takes me to adapt to B less? Or may I have some savings in terms of how long it takes? I think those are two different issues.

DR. LACKNER: Yes. Even in terms of adapting to vertical VOR, it is beginning to turn out that you could make this very context dependent. For example, S.I. Perlmutter and his colleagues oscillated cats on their sides to elicit vertical canal stimulation; simultaneously, he moves the visual display laterally relative to the cat. The VOR will become adapted to that new situation so that if you turn off the lights, the oscillation will elicit horizontal eye movements. But if you turn the animal over on its other side, the oscillation will drive the eyes vertically. So the adaptation is quite specific (see Perlmutter et al., 1987).

DR. EBENHOLTZ: I want to express a word of caution about this. There are examples that seem to indicate that you just do not turn off the adaptation response. Some of them are tragic examples—such as people coming out of training exercises, coming out of pilot training, coming out of simulators, even coming onto shore, and if we had the data, perhaps coming out of tank training—where individuals find that they exhibit what looks like a destabilizing response to a retrained VOR and/or to ataxia. It would seem that some monitoring of the training situation would be very important, at least at the beginning, to know what it is that this training situation is inducing.

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Human Orientation, Adaptation, and Movement Control

JAMES LACKNER

People think of motion sickness as involving nausea and vomiting. I would like to make the point that nausea and vomiting are only two of many symptoms of motion sickness. In fact, as Table 1 (developed by Ashton Graybiel) shows, the nausea syndrome is only one part of motion sickness, and in some circumstances it may not even be the most important aspect of it. Therefore, I want to provide a tutorial about motion sickness and then review things related to motion sickness, so the complexity of the syndrome can be appreciated.

SYMPTOMS OF MOTION SICKNESS

Early on, many investigators thought that there were really two types of individuals: people who showed motion sickness with head symptoms and people who showed motion sickenss with gut symptoms. Head symptoms were thought to include persistent headache or dizziness, drowsiness, and pain. Gut symptoms were thought to include epigastric awareness or discomfort, nausea, vomiting, and so on. The important point is that we now realize that the pattern of symptoms an individual experiences depends on a whole variety of things, not necessarily particular characteristics of the individual per se. The signs and symptoms depend, for example, on the nature and strength of the provocative stimulus, the exposure duration, and the individual's basic susceptibility to that particular type of motion exposure.

Under laboratory conditions, it is relatively easy to recognize motion sickness. You usually use a relatively provocative stimulus, limit exposure durations, and titrate the stimulus intensity so as to elicit motion sickness in a relatively brief period of time. By doing this, you are much more likely to get symptoms that under operational conditions would be associated with exposure to very intense motion. You are more likely to select the kinds

TABLE 1 Diagnostic Categorization of Different Levels of Severity of Acute Motion Sickness

Category	Pathognomonic (16 points)	Major (8 points)	Minor (4 points)	Minimal (2 points)	AQS[a] (1 point)
Nausea syndrome	Nausea III[b], retching or vomiting	Nausea II	Nausea I	Epigastric discomfort	Epigastric awareness
Skin		Pallor III	Pallor II	Pallor I	Flushing/subjective warmth ≥ II
Cold sweating		Pallor III	Pallor II	Pallor I	
Increased salivation		Pallor III	Pallor II	Pallor I	
Drowsiness		Pallor III	Pallor II	Pallor I	
Pain					Persistent headache ≥ II
Central nervous system					Persistent dizziness Eyes closed ≥ II Eyes open III

Levels of Severity Identified by Total Points Scored

Frank Sickness (FS) (≥ 16 points)	Severe malaise (MIII) (8-15 points)	Moderate malaise A (MIIA) (5-7 points)	Moderate malaise B (MIIB) (3-4 points)	Slight Malaise (MI) (1-2 points)

[a] AQS, Additional qualifying symptoms.
[b] III, Severe or marked; II, moderate; I, slight.

Source: Graybiel et al. (1968).

of things that were traditionally thought of as gut symptoms. With such an exposure condition, there are also many other symptoms that the subject is likely not to experience.

In addition, in a controlled laboratory situation, you generally have sophisticated observers who are used to recognizing signs and symptoms of motion sickness, in terms of both the subject's responses and what patterns are likely to be associated with the experiment. Under operational conditions, it is much more difficult to recognize motion sickness. For example, if you have a navigator in an aircraft, it is a clear day, there is a bit of clear-air turbulence, and he feels drowsy, is that drowsiness due to motion sickness or the bourbon that he had the night before? It is often difficult to tell.

Sopite Syndrome

There is one syndrome that has been identified relatively recently, only within the last decade, a syndrome that may well play some part in tanks as they now exist. This is the so-called Sopite syndrome. It was first recognized by Ashton Graybiel around 1978.

The Sopite syndrome refers to the sickness you get with chronic, long-term, low-grade exposure to motion, namely, a feeling of chronic fatigue and drowsiness, a disinclination for work, lack of interest in physical or mental activities, and a lack of desire for participation in group activities. Some people actually show personality deterioration: a kind of chronic fatigue or lethargy, a lack of initiative that does not have any obvious physical basis. People often say, "Well, I'm just bored." They don't realize that, in fact, this is part of a constellation of signs and symptoms characteristic of low-grade motion sickness elicited by a chronic, low-intensity motion stimulation.

The Sopite syndrome may not affect peak performance under conditions of operational stress. What it does do is affect vigilance. We know that it occurs in aircrews, certainly in those at sea, and in railroad crew members. We are certain that it occurs in space flight. As a matter of fact, it may be the case that long after the traditional, more prominent signs and symptoms of motion sickness have abated, astronauts are still experiencing the Sopite syndrome. There is some evidence that it may have lasted for as long as 50 or 60 days in astronauts involved with the Skylab missions.

When I mention air, sea, space, and so on, it is apparent that motion sickness can be elicited by a variety of different types of exposure conditions. One of the more extreme of these is illustrated in Figure 1, which shows a person seated in an absolutely stationary position. However, the floor

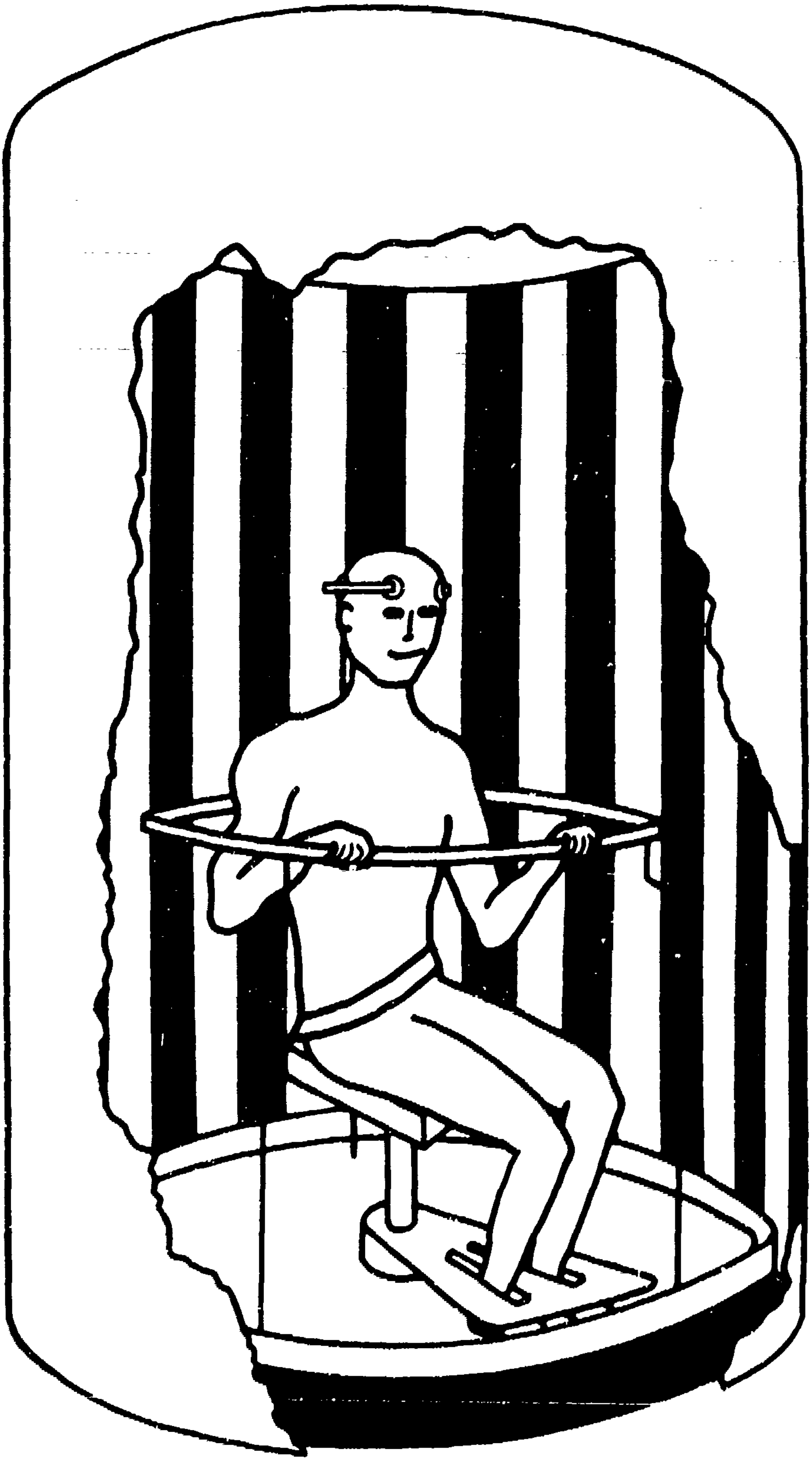

FIGURE 1 Stimulus situation inducing apparent self-rotation. Source: Lackner and DiZio (1984).

can be moved underneath his feet. The position of the feet cannot be changed, so what we are doing, really, is tickling the soles of the feet with a moving platform and tickling the palms of the hands, giving changing somatosensory inputs. In this situation, an individual very quickly feels apparent self-rotation, with his body rotating in the direction opposite that in which the floor is turning. The subject exhibits a nystagmus, that is, a compensatory movement of the eyes, with the slow phase in the opposite direction to the apparent body motion. This experiment is done in complete darkness, and if we have the individual tilt his head so that it is no longer aligned with the axis of apparent body rotation, the subject experiences a sort of rubbery twisting of the body. If the subject's head keeps moving up and down, symptoms of motion sickness are elicited. The only thing that is going on here is that we are rubbing the soles of the feet and the palms of the hands and asking him to make voluntary head movements.

DR. BLAKE: Are the subjects barefoot?

DR. LACKNER: They are not barefoot. They are wearing socks because we don't want to abrade the skin on their feet.

With regard to motion sickness, there is one thing that seems reasonably certain at present; that is, labyrinthine-defective subjects do not seem to be susceptible to motion sickness, although there have been many attempts to make them sick. Labyrinthine-defective subjects do seem to get illusory self-rotation with optokinetic stimulation, but they do not get optokinetic motion sickness.

The failure to make subjects without a functioning labyrinth motion sick implies that the vestibular system is critical for the elicitation of motion sickness. Consequently, I want to give a brief overview of the vestibular system.

Figure 2 shows the position of the vestibular apparatus in the head, including the canals and otoliths. Figure 3 indicates how the otolith organs act as linear accelerometers.

THE ROLE OF OTOLITH ORGANS

The important point regarding otolith organs is that they are influenced by the force of gravity, the vector resultant of gravity, and any other imposed linear accelerations that are present. This relates to an earlier discussion in this report; vertical movements in the tank will affect the magnitude of the linear resultant force. This is an important point, because the otolith organs also affect eye position, as Dr. Ebenholtz mentioned. In fact, you get vestibulo-ocular reflexes (VORs), which tend to drive the eyes up or down,

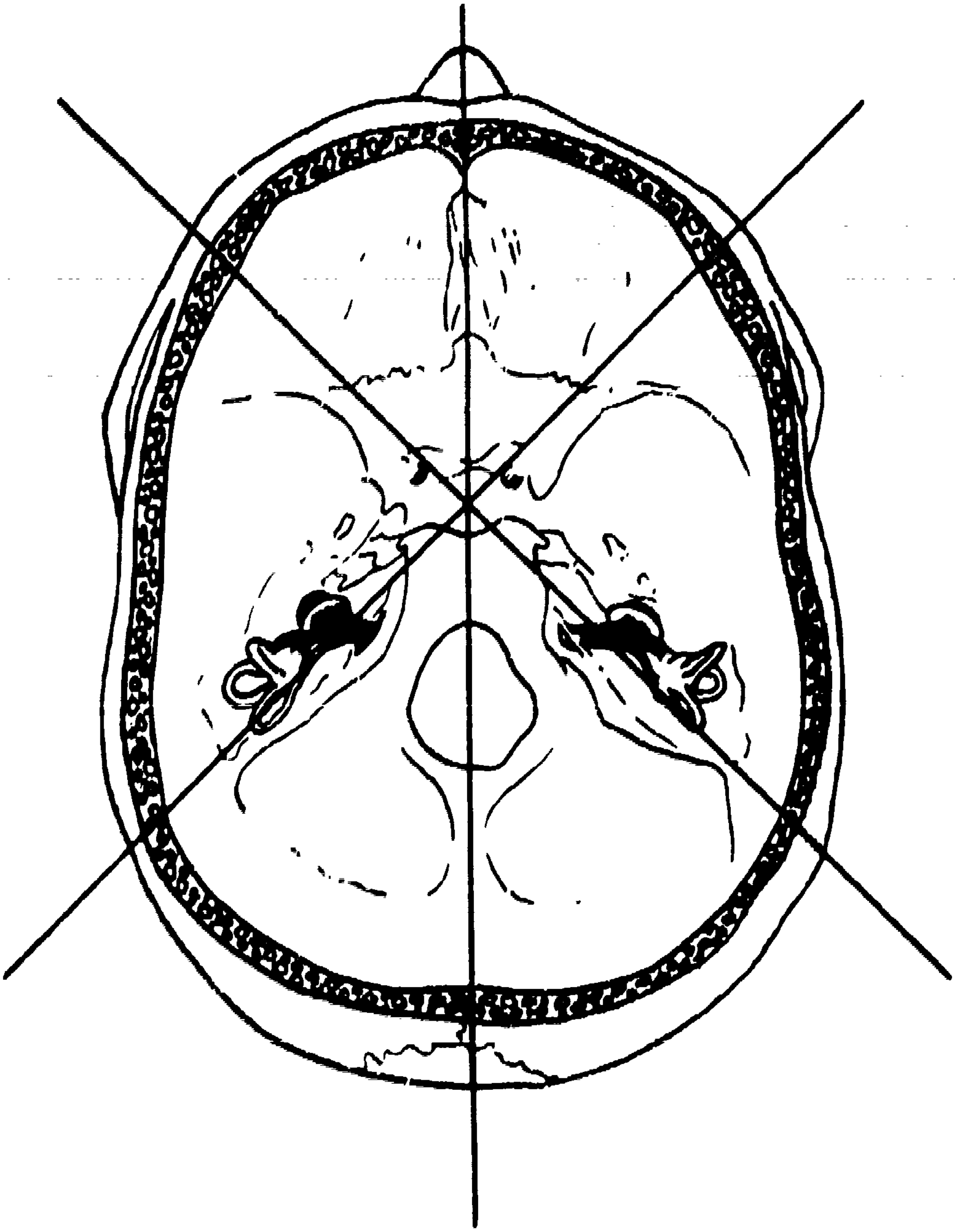

FIGURE 2 Location of the vestibular apparatus in the human cranium. Source: Patterson and Graybiel (1974).

depending on the modulation of the force vector. If you are attempting to fixate a target when that happens, you must override the reflexive vestibular drive.

Figure 4 illustrates a human semicircular canal. Rotation in the plane of the canal is accompanied by a relative lag of the endolymph within the

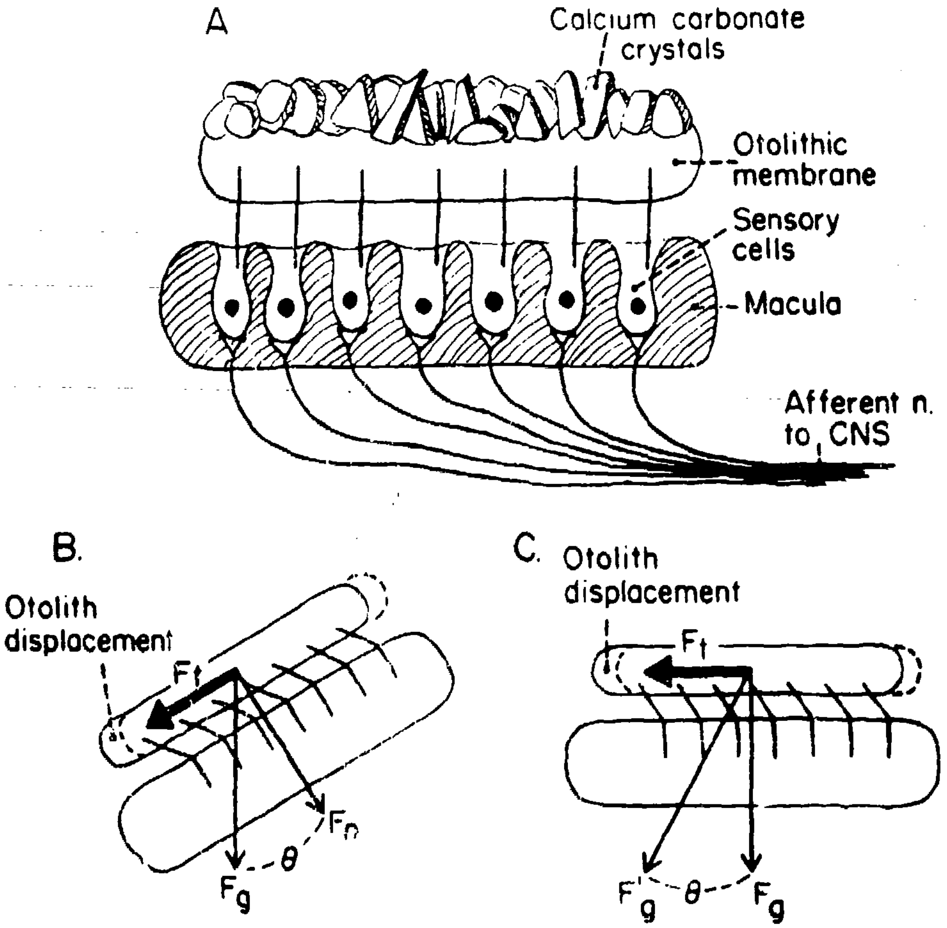

FIGURE 3 Schematic diagram of otolith organs as linear accelerometers. Source: Baloh and Honrubia (1979).

canal. The inertial lag of the fluid deflects the cupula, which gives a signal to the central nervous system. During clockwise acceleration, the right horizontal canal (Figure 5) excites the left lateral rectus muscle and the right medial rectus muscle, which causes the left and right eyes to move in a leftward, counterclockwise direction; the left horizontal canal decreases its inhibition of the right medial rectus and left lateral rectus and decreases its excitation of the right lateral rectus and left medial rectus. This is the classic vestibulo-ocular reflex.

With brief head movements there is essentially a rapid acceleration and a rapid deceleration, so that there is not a prolonged movement of the eyes. By contrast, a long acceleration period elicits a vestibular nystagmus, with the eyes drifting slowly in the direction opposite that of angular acceleration, then repositioning, and then drifting off again.

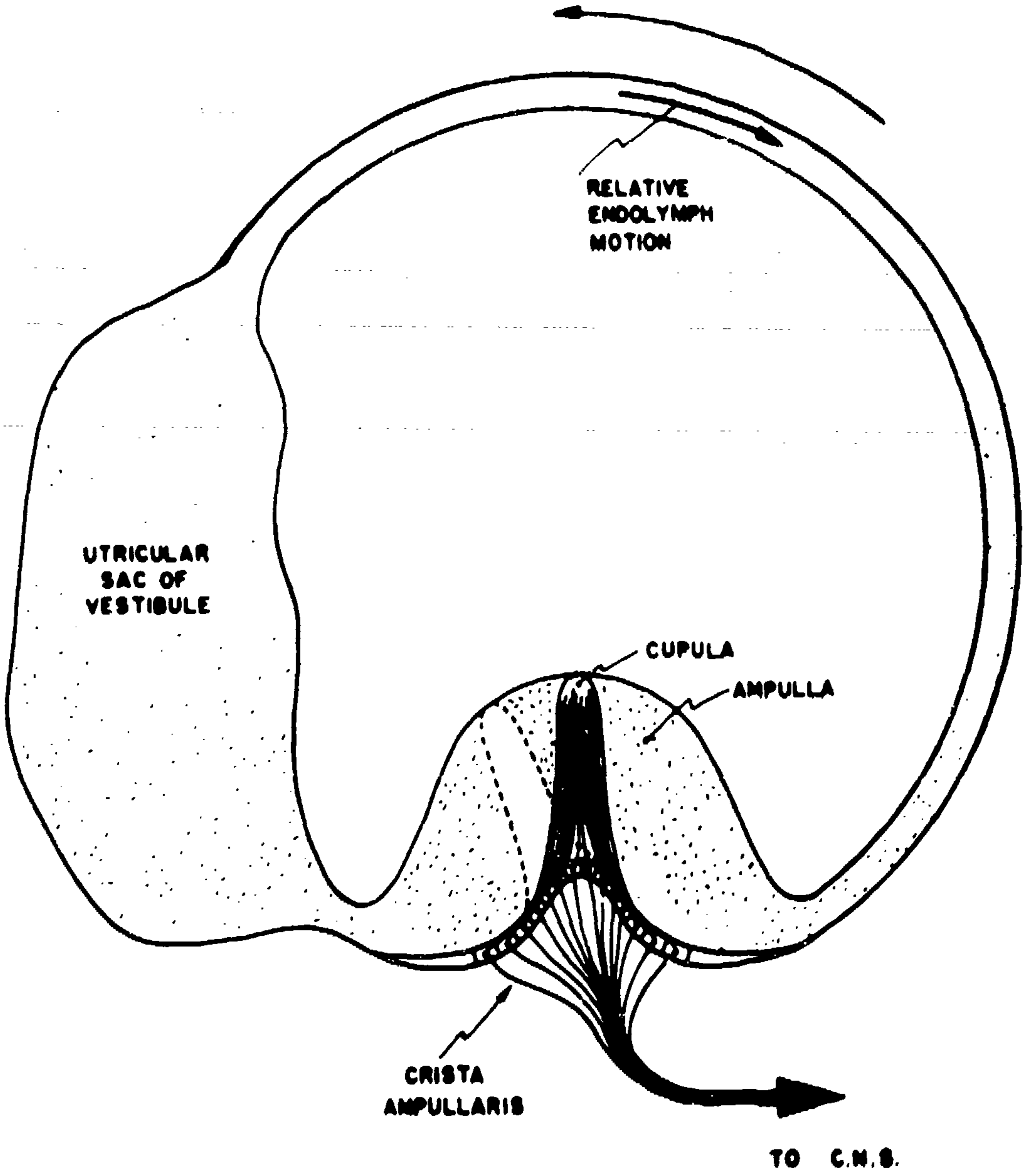

FIGURE 4 Semicircular canal in the human. Source: Baloh and Honrubia (1979).

The otolith organs and the semicircular canals thus affect very directly the control of the eyes and are receptors for the detection of linear and angular acceleration, respectively.

Vestibular Sensitivity and Motion Sickness

Since the vestibular system seems to be so important for the elicitation of motion sickness, people have thought for some time that there may be

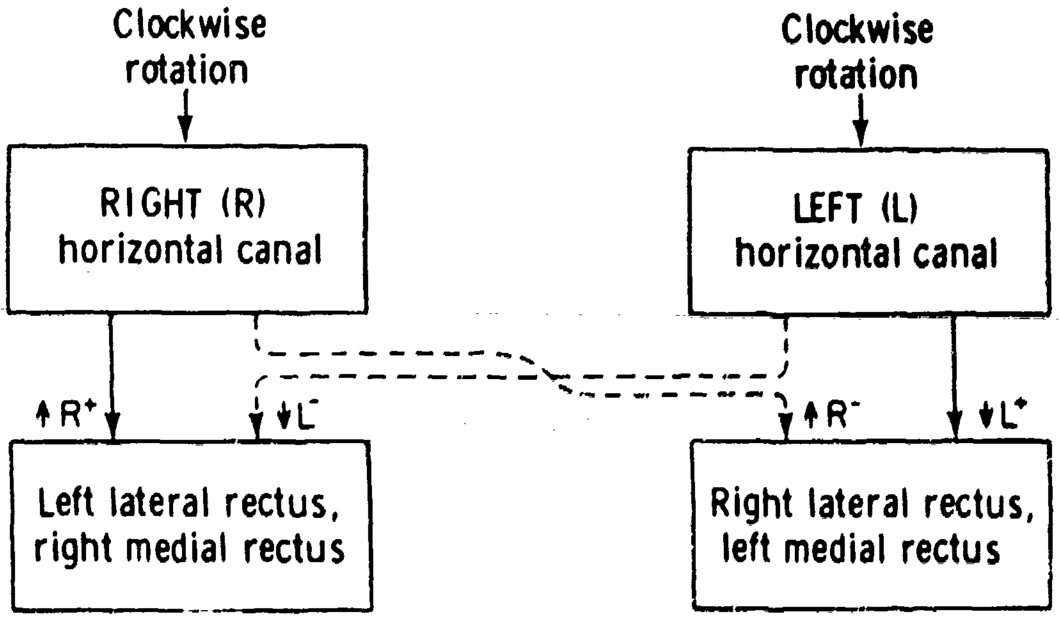

FIGURE 5 Classical vestibulo-ocular reflex.

a simple relationship between the sensitivity of the vestibular apparatus and motion sickness susceptibility. Therefore, scientists have attempted to look at the relationship between measures of the sensitivity of the semicircular canals or the efficiency of the otolith organs and susceptibility to motion sickness. Figure 6 illustrates such a correlation. Figure 6A shows the relationship between the so-called threshold for the oculogyral illusion. This is an illusion that occurs when someone is accelerated, in an angular fashion, and they are looking at a target that is fixed with regard to their body. They will see apparent motion of that target in relation to their body. Sensitivity in terms of perceiving the oculogyral illusion is phenomenal. Subjects see displacement of the visual target long before they can detect any apparent displacement of their bodies. Figure 6B shows the relationship between the detection threshold for the oculogyral illusion and performance on a motion sickness test in which the subject is exposed to off-vertical body rotation.

Off-vertical rotation is a very provocative form of stimulation, and as can be seen, some subjects last only 2 minutes before they reach a nausea endpoint. The important thing to note here is that there is no apparent relationship between the threshold of canal sensitivity, as reflected by the oculogyral illusion, and susceptibility to motion sickness during off-vertical rotation. You might think that there would be a relationship with otolith sensitivity because during constant-velocity off-vertical axis rotation, the otoliths rather than the canals are being stimulated continuously. Figure

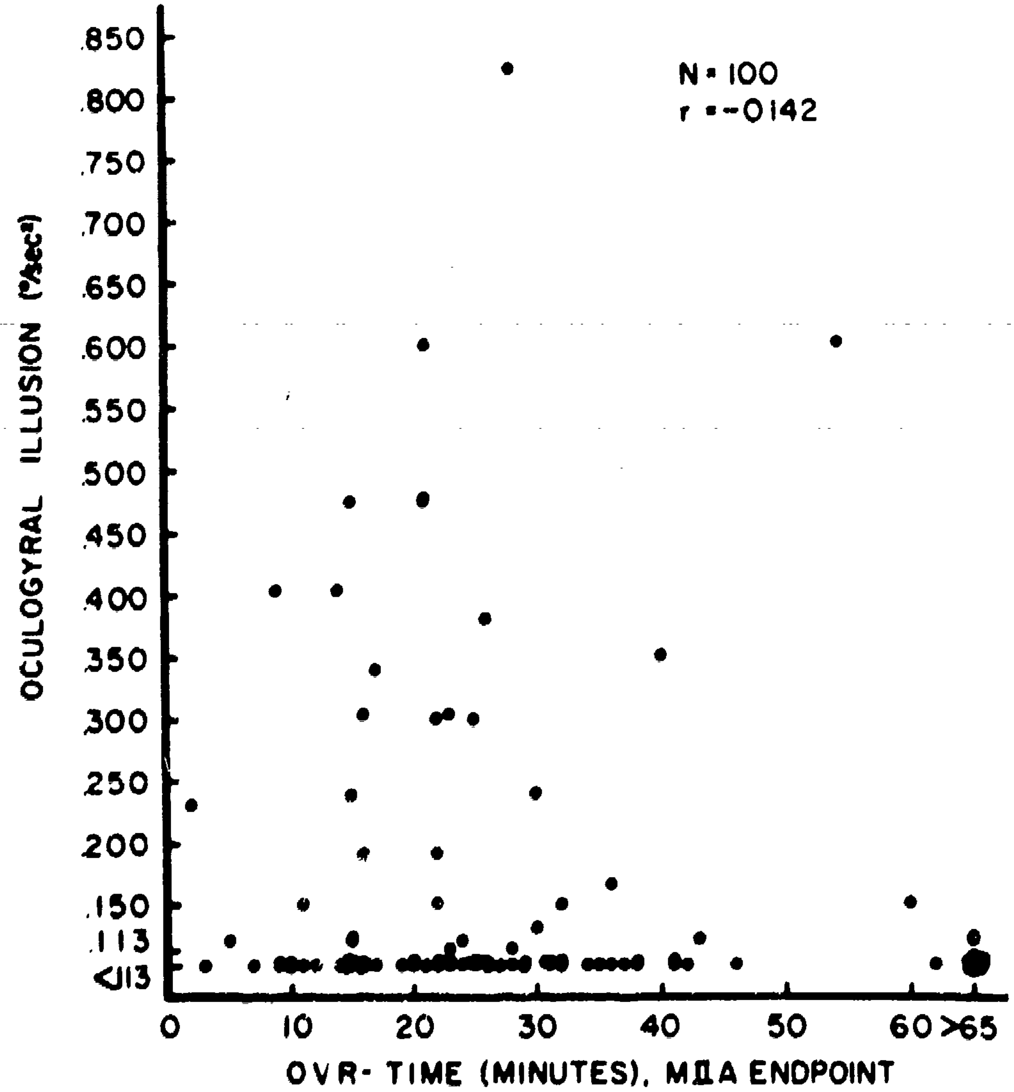

FIGURE 6A Threshold for oculogyral illusion and motion sickness sensitivity. OVR = off-vertical rotation. Source: Miller and Graybiel (1970).

6B indicates, however, that there is no correlation between ocular counterrolling (which is an otolith-driven reflex) and susceptibility to motion sickness during otolithic stimulation.

That leaves us with a problem: in order to measure susceptibility to motion sickness, we are not able to make any predictions simply on the basis of vestibular thresholds. We actually must do a provocative assessment of susceptibility. In other words, if you want to know what the person's susceptibility is, you are going to have to go out and do something to him or her.

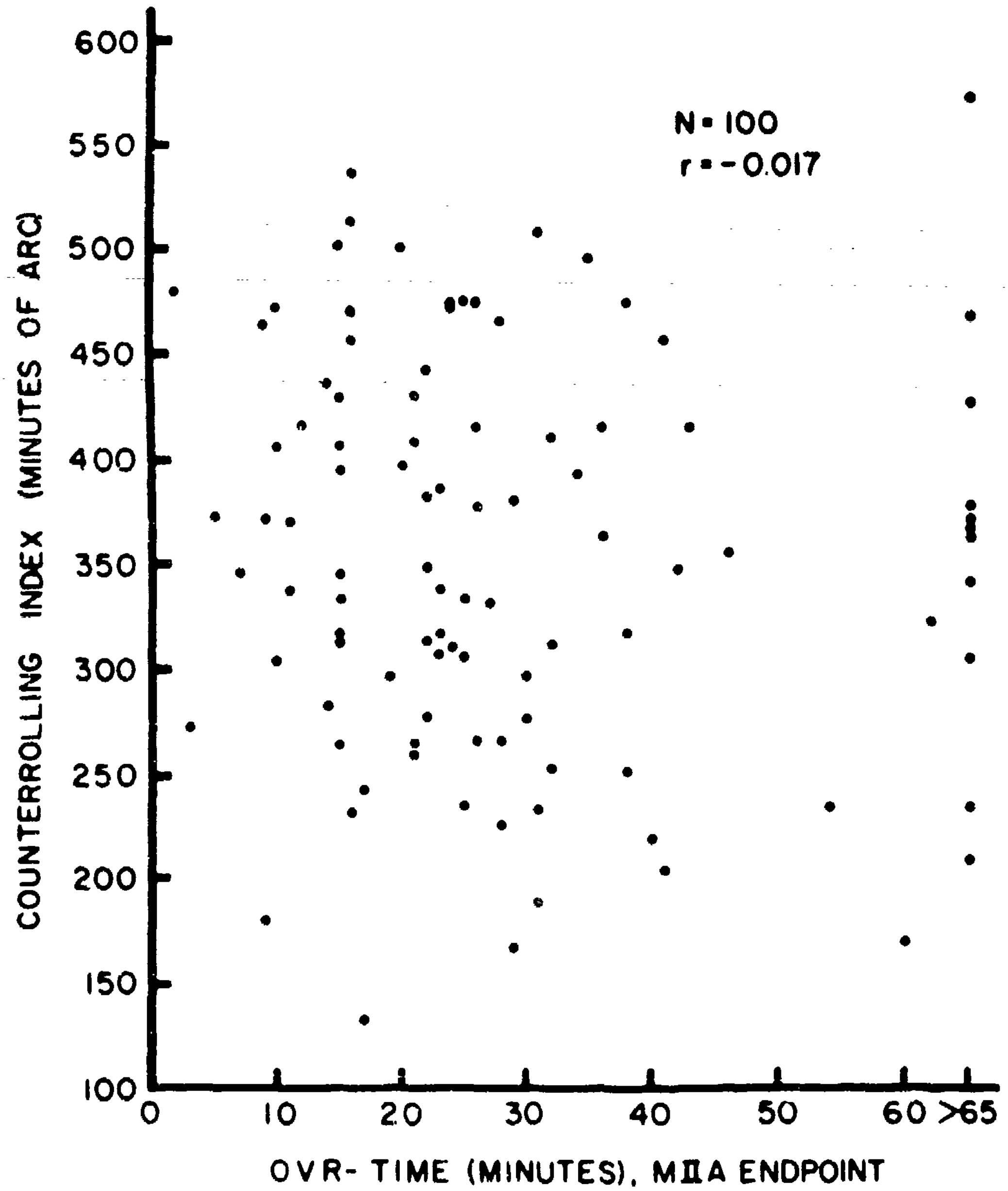

FIGURE 6B Ocular counterrolling index and motion sickness sensitivity. Source: Miller and Graybiel (1970).

Predicting Susceptibility

Isn't it possible that a person who is susceptible to seasickness would also be susceptible to car sickness? Thus, if we measure their susceptibility once, can't we predict their susceptibility in new exposure situations?

A set of correlation coefficients for subjects who were repeatedly tested on a variety of different kinds of provocative motion is presented in Table

2. The first measure involved testing people in a rotating chair using simple angular accelerations. The second one involves caloric irrigation, such as an otolaryngologist uses to see whether the horizontal semicircular canals are functional. (The second one is with eyes closed; the third one is with eyes open.) Notice that these two measures involve purely canal stimulation, although the third measure brings in the effect of vision as well. The fourth measure uses a rotating chair involving on-axis rotation with active head movements. The person is rotating at constant velocity and tilting the head, thus exposing the semicircular canals to cross-coupling. The orientation of the person's otoliths are also changing in relation to the gravitational force vector. The fifth measure involves a slowly rotating room instead of a rotating chair. Active head movements are also involved. The final measure is the off-vertical rotation that I just described.

Many subjects were tested by all of these different procedures. The thing that was disturbing about the findings is that there was only one fairly high correlation, and that was between the susceptibilities in procedures 4 and 5. The problem is that this was the correlation between being in the rotating chair and making head movements and being in the rotating room and making head movements—which are basically the same stimulus to the vestibular system. There is not even a good correlation—as good a correlation as one would hope—with situations that presumably involve simple canal stimulation. One cannot even generalize with certainty from one configuration involving stimulation of the canals to another. The point, then, is that this lack of strong correlation horribly complicates the selection of tasks that might be used to predict susceptibility in different motion environments.

DR. KENNEDY: Why do you say that it gets more complicated? You have strong probable correlations. Although the things being measured are not as reliable as you would like, you would probably account for half the variance in one thing by measuring the other thing if you adjusted the relationships based on known unreliabilities.

DR. LACKNER: That would help only if you were going to select large numbers of people.

DR. EBENHOLTZ: What is the reliability of the same measure of the same condition?

DR. LACKNER: We have done that with a test known as the sudden stop test (Table 3). This is a procedure in which we accelerate people up to a constant angular velocity of 300 degrees per second and we then put on the brakes. We wait 30 seconds and repeat. We do that 20 times with the subject blindfolded and then take the blindfold off. If the person lasts 20 more times before getting nauseated, we reverse the direction of the

TABLE 2 Correlations Among Susceptibility Ranked by Several Tests of Motion Sickness

Procedure	Upright Angular Acceleration Without Head Movements, Eyes Closed (AAS)	Upright Bithermal Irrigation, Eyes Closed, No Movement (BIS E/C)	Upright Bithermal Irrigation, Eyes Open, No Movement (BIS E/O)	Upright Constant On-Axis Rotation With Active Head Movements, Eyes Closed (CAS-Chair)	Upright Constant Off-Axis Rotation With Active Head Movements, Eyes Open (CAS-SRR)	Tilted Off-Vertical Rotation Without Head Movements, Eyes Closed (OVR)
AAS		0.60	0.57	0.71	0.56	0.75
BIS E/C			0.69	0.33	0.31	0.32
BIS E/O				0.75	0.74	0.19
CAS-Chair					0.93	0.55
CAS-SSR						0.35
OVR						

Source: Miller and Graybiel (1972).

TABLE 3 Number of Sudden Stops Tolerated by Subjects in Four Experimental Sessions

Subject	Test Order	EC/EC	EO/EO	EC/EO	EO/EC
RD	3-4-1-2	11	4	4	4
JD	3-4-2-1	18	13	19	40
JR	2-1-3-4	19	11	27	30
JF	4-3-2-1	40	13	13	12
WG	1-2-3-4	40	17	12	13
RF	4-3-1-2	40	10	12	12
RM	2-1-4-3	40	40	40	40
GH	1-2-4-3	40	11	28	30
Average		31.0	14.9	18.1	22.6

Note: EC/EC, Eyes closed throughout test; EO/EO, eyes open throughout test; EC/EO, eyes closed during acceleration and constant velocity but open during sudden stop; EO/EC, eyes open during acceleration and constant velocity but closed during sudden stop. Numerals 1, 2, 3, and 4 under test order refer to EC/EC, EO/EO, EC/EO, and EO/EC, respectively; their order specified the test order, e.g., 3-4-1-2 is a EC/EO, EO/EC, EC/EC, and EO/EO testing sequence.

Source: Lackner and Graybiel (1981).

rotation. If you test people repeatedly by that procedure, you find that the first test is not a very good indicator of later susceptibility. The second and third tests are very reliable.

DR. WHITCOMB: What about biographical information? Is that reliable?

DR. LACKNER: I want to make one point regarding questionnaires. One of the last things that Ashton Graybiel was working on at Pensacola, Florida, before retiring was a study of motion sickness among Navy referrals. He did a sneaky thing. He went back to their original records and got the motion sickness questionnaires that they had filled out and compared the results of his interview with their answers on the questionnaires. In fact, he wrote a paper called "Fibs and Lies," which he never published.

As it turned out, among the 20-some motion sick Navy referrals that he dealt with, every single one of them had, in fact, falsified their questionnaires—in very extensive ways. They had sometimes had to fill out more than one questionnaire, and it turned out that they did not even lie consistently.

TABLE 4 Number of Subjects Who Reported Symptoms Characteristic of Motion Sickness During and After Exposure to Optokinetic Stimulation in the Fixed-Head and Moving-Head Conditions of Experiment 1 (N = 10)

	Fixed-Head		Moving-Head	
Symptom	Trial	Post Trial	Trial	Post Trial
Dizziness	5	5	5	5
Drowsiness	0	2	0	2
Epigastric disturbance	2	3	2	2
Headache or eyestrain	2	6	0	0

Source: Lackner and Teixeira (1977).

Passive Exposure

Passive exposure to a changing visual array can be provocative, often as provocative as if you are looking at the display and also moving your head. Notice the kinds of symptoms that are reported in Table 4 (these results come from a study done nearly 10 years ago).

It is important to note that it is often the case that, after the exposure condition is over, symptoms such as headache or eyestrain can be reported. Many of the symptoms listed in Table 4 are more the kinds of symptoms that I referred to as head symptoms earlier on. This includes dizziness, drowsiness, headache, and so on. They occur in the absence of any motion of the individual whatsoever, that is, simply with motion of the eyes. It does not seem that voluntary movement of the head makes it a lot worse; on the contrary, in some cases it makes it better.

In the sudden stop procedure I referred to earlier (Table 3), notice what is happening when you accelerate someone up to constant angular velocity and then put on the brakes. You are giving the subject a very powerful stimulation of the semicircular canals. Canal stimulation, if it is repeated often enough, is provocative. As a matter of fact, some of our people can only withstand six or seven of those sudden stops without becoming nauseated. So, a very strong vestibular stimulus can make a subject sick quite readily.

One of the things that we looked at—which is relevant to the issue of a moving vehicle and a moving display—is the issue of stopping suddenly with your eyes open throughout the procedure. What we found was that people are least susceptible to motion sickness when the have no vision whatsoever. Having the eyes open throughout the procedure is most provocative, but it [illegible] that if the eyes are open open at any point during the procedure, it enhances one's susceptibility. It really makes it much worse, in fact. This finding raises a problem for the use of visual displays when there are moving elements in the display while the vehicle is also moving—moving up and down as well as turning in an angular fashion.

One of the people who has looked at this problem in some detail is Fred Guedry. Guedry conducted a series of experiments that are extremely interesting for the problems being discussed at this conference. Guedry asked the following question: Suppose that we expose an individual to angular oscillation, and at the same time we place a display in front of him that moves with him. We ask him to scan it and to call out different elements and to identify different components within that display. What happens?

It turns out that this is one of the nastiest things you can do to someone. It is extremely provocative. It is less provocative to have the display stabilized with respect to the environment while you are moving and attempting to scan it and pick components out, but it is still very provocative. Consequently, we can expect that in any situation in which a vehicle is moving and the occupants are undergoing angular or linear acceleration and attempting to scan a display—whether it is a display that is externally anchored or one that is moving with the motion of your body—the occupants in all likelihood are going to find it provocative.

DR. EBENHOLTZ: Are you seeing any effect of oculomotor systems, either to track or suppress?

DR. LACKNER: Yes. Let me amplify. Exposure to constant angular acceleration in darkness leads your eyes to exhibit a compensatory nystagmus for the reasons that we went through before. The vestibular input should be constant, regardless of whether the person attempts to move his eyes voluntarily or not. While the person is in total darkness, there is an oculomotor component as well as a vestibular component.

Suppose I am exposed to a clockwise angular acceleration, the slow phase drift of my eyes will be counterclockwise and they will beat back to the right. If I try to deviate my eyes in the direction of the fast phase, the following will happen: the slow-phase velocity of my eyes will increase, the slow-phase amplitude will increase, the fast-phase amplitude will increase, but the beat frequency will not be affected. In many people, symptoms of vertigo and motion sickness will be elicited. If you attempt to look in the direction of the slow phase, you find it uncomfortable because any attempt to maintain the eyes to that side gives some discomfort, but it is not provocative in the same way.

DR. BLAKE: In what period of exposure?

DR. LACKNER: This is with angular accelerations from 6 to 20 degrees per second squared, angular acceleration ramps for 6 to 20 seconds, and then there is constant velocity and then a deceleration to a stop. The discomfort occurs within seconds and is quite distasteful. I think it may relate to some of the things that were mentioned earlier about prolonged optokinetic stimulation and motion sickness. We are thus finding that symptoms are elicited when you are trying to prevent a vestibularly driven eye movement. We have reason to believe that the same thing would happen if you were trying to suppress an optokinetic input by fixating a target line.

DR. HELD: I wondered if these observations relate to the fact that, if you are on a ship in a storm, you will do better if you get out and watch the horizon.

DR. LACKNER: I am not sure, although this has not been investigated. We know that this helps in situations in which there is self-motion and you have visual stability of the environment. The other thing that probably helps is that you are probably also anticipating the motion of the boat better when you are on deck.

Another very important point here from the standpoint of motion sickness is the extent to which the individual has control over the input. Here I think that the key is not only the sort of vestibular input, but also the optic input. So that motion within displays, which is uncorrelated with anything done by the individual, creates situations that tend to enhance motion sickness.

REDUCING MOTION SICKNESS

It turns out that cueing to decrease motion sickness can be achieved in a variety of ways. Let me give some examples. We were talking about how provocative sudden-stop stimulation can be. Rolnick and I did the following set of experiments. We were aware that in airplanes the pilot tends not to get sick whereas the navigator does, and that the driver of a car tends not to get sick but the passengers do. The point is that the person who is controlling or anticipating the motion becomes sick less often than the passengers. So Rolnick and I asked the following question: What happens when an individual controls vestibular input?

To test this, we created a device that provided a crank that a person could turn. It was a rheostat hooked up so that it drove the servo on a short-arm centrifuge. By turning the crank, a signal was generated proportional to the rate at which it was turned. Then, at some point, the operator stopped turning the rheostat and the motion ceased. We recorded that signal on tape and later played the same input back without the subject controlling it.

We found that very different responses were evident in the two situations. When the subjects generated that input themselves, it made them less susceptible to motion sickness. The subjects also had a shorter aftersensation of rotation than did subjects in the passive condition.

We then wondered whether the response was somehow related to the person's own active generation or knowledge of the input. We had two people ride on the short-arm centrifuge together; one person turned the crank and the other person just sat there.

We found that the person who went around for the ride got sick, much sicker, than the other, active person. We then had the person who was being passively displaced rest his hand on the person's hand who was turning the crank. We found that there was no difference between the two individuals, that they were both less susceptible than when they received only the input without any knowledge about their motion.

What this suggests is that cueing in some form may be useful for different members of the tank team, depending on whether they are initiating the motion or whether they are simply being exposed to the motion, the motions of both the turret and the visual display.

DR. EBENHOLTZ: Was head position fixed in this study?

DR. LACKNER: Head position was fixed, yes.

DR. LEIBOWITZ: In the case of the passive person, would the cues be prominently cutaneous and kinesthetic, not muscular or little muscular feedback?

DR. LACKNER: It is hard to get a truly passive movement because you really have to learn to relax the arm. We asked the subject simply to rest his hand and let it be carried along. One of the people in my lab is trained as a physical therapist. We have talked a great deal about the problem of the passive head movements that we are attempting to achieve in our rotating room. We are also recording electromyograms from sternocleidomastoids and trapezius muscles because we want to make sure that we are getting real relaxation. I am not certain at the moment, at least with regard to the control of the head, that you can achieve full relaxation.

The other point I want to make here is that we have come to realize that joint receptors are much less important for position sense than we had previously thought. Spindle input tends to be tremendously important. If you have a completely relaxed arm which is not moving at all and you record from the muscle spindles, you see they are virtually quiescent. There are various illusions of position and degradation of position sense that occur in a limb that has been stationary for a long period of time. These may be related to the low level of spindle discharge.

In fact, one of the things that we have been looking at in parabolic flight experiments is the modulation of spindle input by the vestibulospinal reflexes as a function of gravito-inertial force level. We find that there are changes in position sense and there are changes in movement control that occur virtually immediately. When you are weightless, you do not need your antigravity musculature in the way that you do under normal 1-*g* conditions. There also seem to be immediate changes that occur to modulate the activity level of oculomotor and skeletomuscular control. These changes have consequences for the position sense of your limbs until you recalibrate.

DR. EBENHOLTZ: Do you have some evidence on the role of mental alertness? There must be some difference in mental attitude or alertness in modulating the signal coming from the vestibula.

DR. LACKNER: It has been known for a long time that things like mental arithmetic affect myotactic reflexes; for example, you can affect the intensity of a knee-jerk reflex simply by modulating the individual's state of alertness. The same is true for vestibulo-ocular reflexes. We control for alertness in all of these experiments because we know it is a key factor.

DISPLAY REALISM

Another point that has not been discussed is the issue of realism in visual displays. If you are in a vehicle that is moving over terrain, one of the things you need is adequate realism of the terrain in your visual displays to be able to anticipate bumps and jolts. In other words, if the individual is able to anticipate variations in the ride, the likelihood of motion sickness is decreased. Realism likely makes a major difference. The direction of motion of the vehicle, as well as the direction of representation of the environment within the visual display, is critical. The individual should know his orientation in relation to the direction of motion of the vehicle and be able to anticipate variations in the ride of the vehicle. Otherwise, not only will motion sickness tend to result but various kinds of disorientation may also occur.

There are various ways to indicate to a rider what his position is in relation to the direction of motion of the vehicle. The Malcolm horizon, for example, has proven to be tremendously helpful in terms of orientation in aircraft. This device is a laser line of light that is scanned across the cockpit, and, regardless of the orientation of the aircraft with respect to the ground, the line is parallel to the true horizon. A pilot who is using it quickly forgets its presence. Yet, it seems to anchor his orientation so that the tilt sensations themselves seem to abate. I don't know whether it would be possible to develop the same sort of cueing mechanism for use in tanks, but the idea is potentially a good one.

ILLUSORY SELF-MOTION

One other factor that we must be concerned about with visual displays is the possibility of inducing illusory self-motion. Wide-angle displays with moving scenes can do this readily. Moreover, if a person is in a near-recumbent position—as the driver of a tank is—some additional distortions can occur. Figure 7 shows a recumbent person looking at a rotating visual array that is horizontal above him. If the display is rotated, the individual will soon come to perceive it as stationary and himself as rotating (in the opposite direction to the disk's actual motion) in 360-degree circles about his optical axis.

However, if his head is tilted up 30 degrees and the disk back is tilted up 30 degrees, so that its surface remains perpendicular to the optical axis, several changes result. The person soon comes to feel as if his head is again horizontal, and he sees the disk as horizontal rather than tilted. Simultaneously, he experiences rotation of his body about the optical axis. Accordingly, not only the sense of body and visual motion have been affected but also the orientation of the head in relation to gravity and to the torso, as well as the apparent orientation of the visual display to gravity. Such perceptual remappings have considerable implications for vehicular control.

Other distortions can involve the apparent dimensions of the optical display. For example, if an individual is standing upright, but off center, in an optokinetic drum, and then if the drum is rotated, he not only experiences illusory self-rotation in the direction opposite actual drum rotation but also sees the drum as being of a different size.

The individual feels that he is in a drum of sufficient size for him to be at the center of rotation; as he begins to experience self-rotation, the drum seems to change its size. It seems to get big enough to put him at the center of rotation.

DISCUSSION

DR. LEIBOWITZ: So the stripes must look narrower if they are farther away.

DR. LACKNER: No, they look wider because they follow the visual angles.

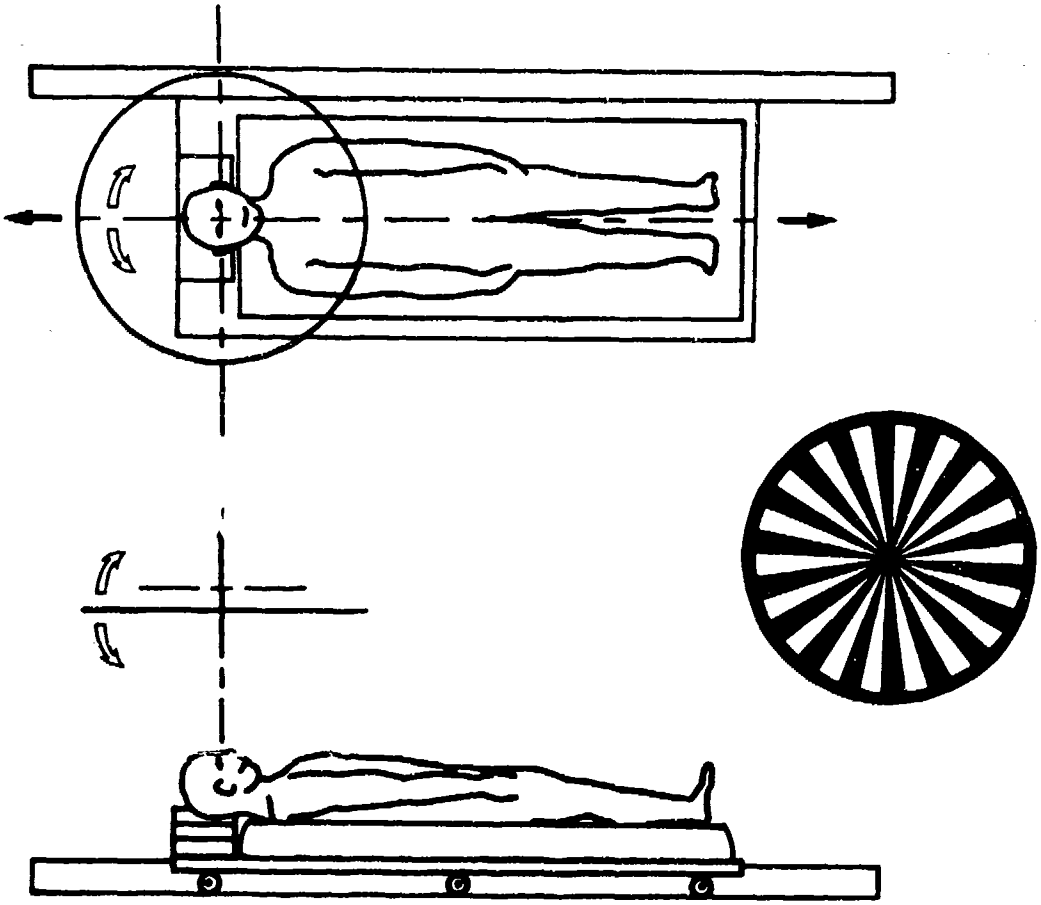

FIGURE 7 Recumbent observation of a rotating visual array. Source: DiZio and Lackner (1986).

What this task does is to create a full-body situation in which the visual array, the visual surround, and what the body is perceived as doing are consistent with the pattern of semicircular canal input, the pattern of otolith input, and the pattern of muscular input. It does so by remapping.

One of the things we are looking at now is whether this happens in seated subjects.

DR. HYMAN: This same situation may be a problem in the present fire-control system for the gunner, which has the gunner in the turret. When he is rotating the turret, he is rotating at varoius angles. But when he has a 3-degree angle of subtense that obscures the view, with the weight of motion and magnification of his display, he may feel that he is rotating at a fast-angle arrangement when, in fact, he is turning at a slow angle.

DR. LACKNER: My guess is that these people must adapt to that situation. My guess, also, is that a full day in a tank is very stressful. The crew members are probably quite tired when they have finished the day, and I feel that there is a fair amount of motion sickness that probably is not being recognized as such. It is probably more a low-grade Sopite syndrome. My guess is that adaptation is taking place during the course of training. It is probably much easier after they have had extensive training, but if they have a period of inaction and have to come back, for example, after 3 weeks or a month, my guess is that some readaptation is necessary.

DR. LEIBOWITZ: If I recall the comments made by Sargeant Womer at our last meeting in 1987, after he has been in the tank for a while and leaves it, he waits a while before he drives home.

DR. LACKNER: I remember that and I thought at the time that this may be significant and related.

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Reconsidering Human Factors Engineering Criteria for Armored Vehicle Design

ROBERT KENNEDY

Within the scope of armor training, there is a pertinent set of documents that deals with the tank commander and his job (Drucker and O'Brien, 1981). This paper describes the tasks of the tank commander (Table 1), as well as the leadership tasks. A similar description of the tasks of other members of the crew, the gunner, the driver, and the loader, are listed in Table 2.

DESCRIBING THE NEW SYSTEM AND ITS ELEMENTS

The old system consisted of a tank commander, gunner, driver, and loader. The ideal system has a tank commander, a driver, and a gunner. The loader's task is performed automatically. The old system has tracks; we don't know about the new system. It may have tracks; it may be air cushioned; it may have surface effects. The inertial environment, therefore, is as yet unspecified.

The viewing requirements in the old system include direct-viewing possibilities, optical possibilities, and binocular possibilities. In the new system, the viewing requirements may be electronic, color, and/or holographic, but they may not involve an outside view. They may have wide or narrow fields of view. They may involve electronic displays, which raises questions about realism (how much or how little?), fidelity (how much or how little?), and what is nauseogenic?

With respect to the human factors engineering issues, we must start with the operational requirements of the vehicle.

The operational requirements and emerging technologies that allow us to focus on the new systems' designs are shown in Figure 1. A more sophisticated presentation would have a filter with specific characteristics instead of just an arrow, but this makes the point linear. The criteria for

TABLE 1 Tank Commander Leadership Tasks

Task Number	Task Description
1	Acquire targets
2	Analzye and utilize terrain
3	Announce feeding and rest plans
4	Assign sectors of observation
5	Clarify mission
6	Identify and select tank targets
7	Ensure maintenance
8	Post air and ground guards
9	Select and prepare alternate position
10	Prepare and complete battle position
11	Direct cease-fire
12	Ensure communications check
13	Maintain correct interval with other tanks
14	Direct main gun to be oriented
15	Carry out movements in formation correctly
16	Ensure that readiness actions are conducted
17	Direct rapid movement into assignment area
18	Direct tank be camouflaged
19	Engage surprise targets
20	Engage targets in assigned sector
21	Identify withdrawal route
22	Initiate range card preparation
23	Request, monitor, and adjust indirect fires
24	Prepare for three-man crew operations
25	Provide supply and maintenance status to platoon leader
26	Report personnel status
27	Select good fields of fire
28	Shift fire on order
29	Submit SITREP
30	Submit SPOTREP
31	Tie in tank with elements on left and right
32	Wait for order to open fire

Source: O'Brien and Drucker (1981).

this system include operational efficiency, lethality, and survivability. Other criteria may be cost, maintainability, user acceptance, the minimization of training, safety, and health. All these considerations drive the design of new systems.

Coupled with these, there are the characteristics of the user population. This comprises another filter or a set of constraints in which visual capabilities, as well as cognitive and information-processing capabilities, size of the driver, and susceptibility to motion sickness, are important.

In the past the tank commander's job was heavily visual. The new tank commander's job may not be as visually dependent, but instead, it may be more cognitive. The new systems are becoming more complicated

TABLE 2 Selected Tasks of Armor Crew

Crew Position	Task Description
Gunner's area	Boresight the gun correctly
	Index the prescribed ammunition and range in the computer
	Reconnect the loose wire in the electrical firing system
	Correctly use the ACUTE procedure in chekcing turret power
	Correct or report the difficulty which caused the turret power to malfunction.
	Report the defective gunner's quadrant
	Clean the dirt from the air cleaner
	Clean the dirt from the periscope lens
Driver's area	Reconnect the loose spark plug wire in the main engine
	Release or report t[illegible]sed choke in the auxiliary engine
	Replace the missi[illegible]gs in the track and suspension system
	Add crankcase oil [illegible] auxiliary engine
	Replace the portable fire extinguisher in its bracket
	Replace the burned-out bulb in the headlight
	Report the defective gas cap
	Check that the radio is off before starting the main engine
	Test the signal light and adjust the volume for the external interphone
	Clean the dirt from the driver's periscope
Loader's area	Report the shortages in 90-mm and .30 caliber ammunition
	Stow the ready rack with the prescribed numbers and types of rounds
	Replace the missing clamp on the ready rack
	Replace the blown-out fuse in the tank radio
	Tune the radio to the prescribed primary frequency, and adjust the squelch and volume correctly
	Correctly adjust the headspace and solenoid on the .30 caliber machine gun
	Bleed the excess replenisher oil from the recoil mechanism
	Check the transmission fluid with the engine idling

Source: O'Brien and Drucker (1981).

because the loader position has been dropped out. The characteristics of visual contrast sensitivity and spatial frequency may be varied in the new system. These changes, in turn, may drive those emerging technologies while deleting the operational requirements. We are also considering including a tactical display system (Figure 2) in the tank. The operator may be reclined or he may be upright. If he is reclining, the display may be an optical or telegraphic display. If it is optical, it may be small, large, monocular, or binocular; but there may only be one or two of them. Aaron Hyman had 17 displays (described elsewhere in this report).

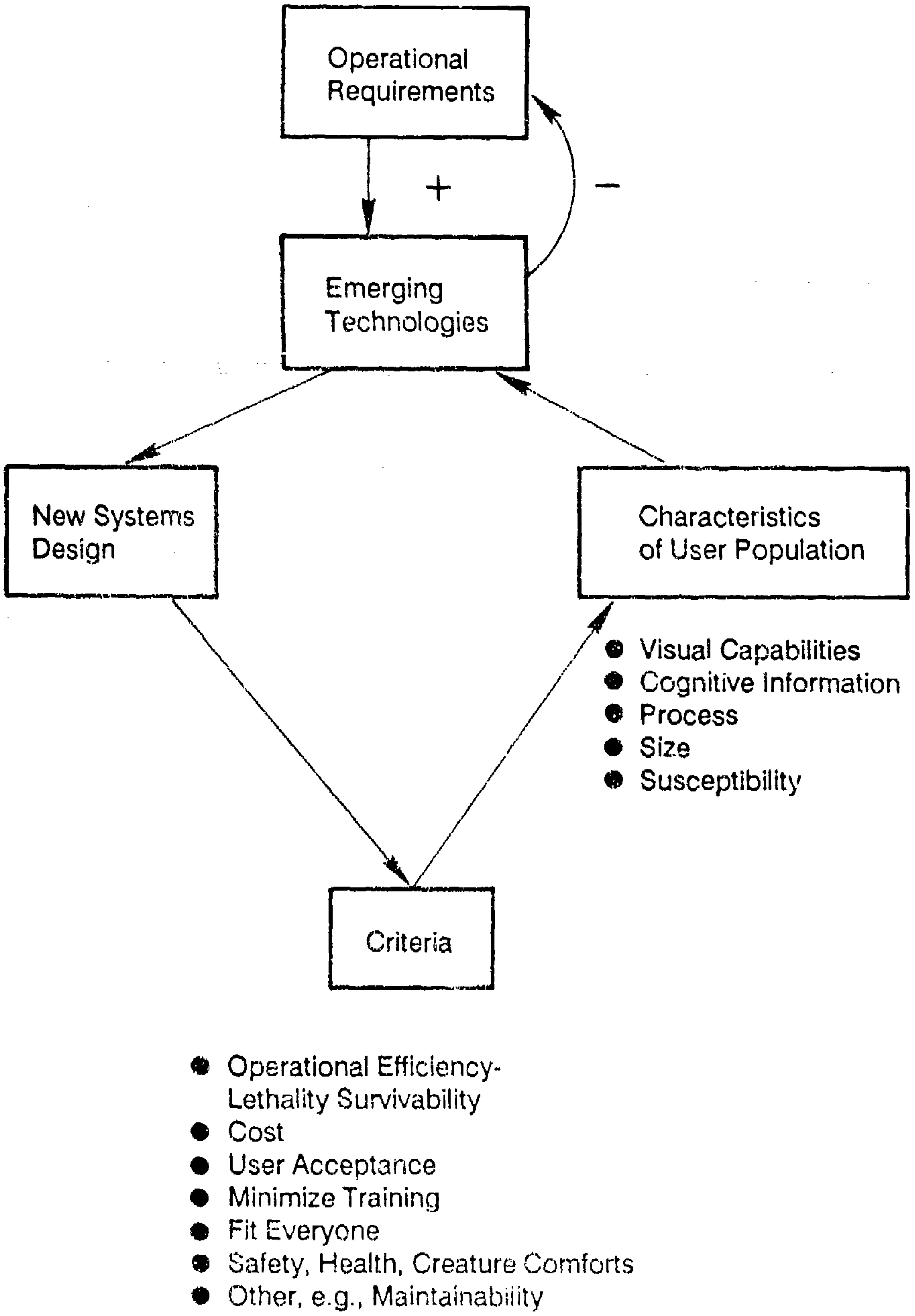
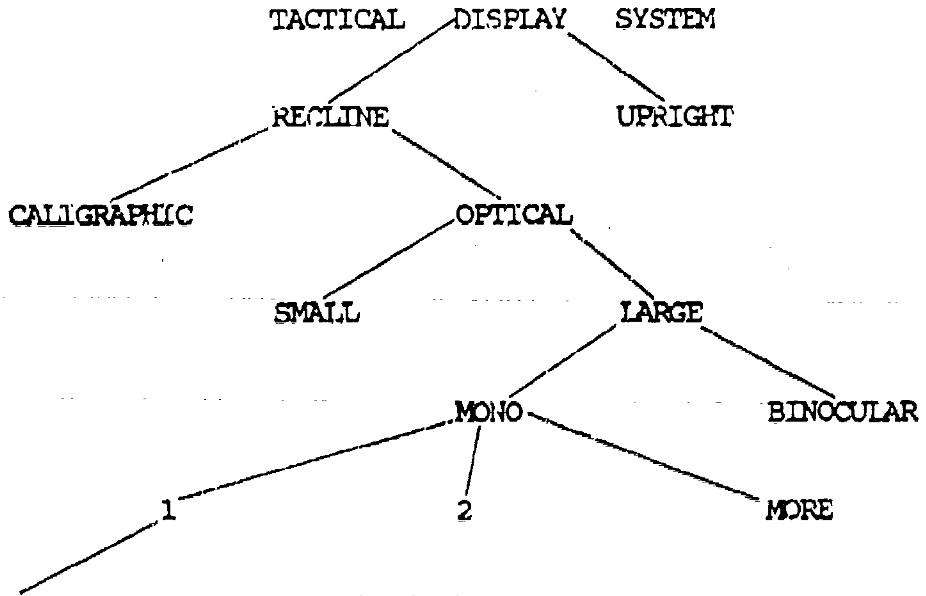


FIGURE 1 General tasks of the tank commander.



PERFORMANCE ISSUES	MOTION SICKNESS ISSUES
Detection	Asthenopia
Recognition	Distortion
Aiming	Vection/Velocity--OKN
Designation	Bore Sight with Inertia
Ranging	VOR Recalibration
Kill	Efferent Control
	VLF (.2 Hz)

FIGURE 2. Complexity has an impact on understanding the operational requirements of the armored vehicle. OKN = optokinetic nystagmus; VLF = very low frequency; VOR = vestibulo-ocular reflex.

Display system considerations give rise to two different kinds of issues, one of which has to do with performance: Is the operator able to perform his task? To arrive at the answer we may need to address a separate set of issues involving target detection, target recognition, aiming, and so on. Those issues are different from the criteria that may determine whether a tactical system is nauseogenic (that is, produces motion sickness).

DESCRIBING MOTION SICKNESS ISSUES

If the only charge to this working group was to discuss or address those issues that produce motion sickness, then we would say that motion

TABLE 3 Factors Contributing to the Occurrence of Motion Sickness Arising From the Use of Electronic Displays

- Asthenopia
- VOR recalibration
- Wide FOV-vection
- Refresh rates
  - Flicker (large field)
  - Asynchrony and lags
- Distortion
- Background agrees with foreground
- Background agrees with inertia
- Position in vehicle
- Bore sight veridical with position
- Depth Illusions
- 0.2-Hz Resonances
  - Inertial
  - Visual

sickness can be presumed to (and will) influence performance. But that issue is problematic. There is not a lot of experimental evidence that says that this outcome will result. Motion sickness is certainly undesirable. In terms of formal, direct influence on performance reduction, however, the amount of data is scanty and imperfect.

Table 3 lists some of the factors that contribute to motion sickness arising from the use of electronic displays. We have the capability to produce displays that are not what you see when you look directly at the scene. When this is the case, a whole new series of potential motion sickness issues may surface. If the display moves with you in ways that are different from the way the real ones do, there may be a vestibulo-ocular reflex (VOR) recalibration. A wide field of view can have certain kinds of peculiar problems. Refresh rates are also a consideration. We think that perhaps large-field flicker may be different from small-field flicker, and large-field flicker may be interpreted in peculiar ways as if it were motion in the background. The sickness or the discomfort reported from flicker may be a nauseogenic stimulus. Does the background agree with the foreground? Does it agree with inertia? Does it agree with anything? Is it veridical? That is, am I bore sighted with what I am seeing or am I offset? Do I have two displays? Should the driver and the tank commander share the same bore sight?

Does the depth create depth illusions? This may change if it is a monocular display. What about use of 0.2 Hz—a very nauseogenic frequency? New systems, if they are air-cushioned systems, may have a lower frequency of oscillation than we have now. We may have "seasickness" in tanks. There is good evidence that the amount of acceleration at 0.2 Hz is bad for people, whether they are enclosed or not. The evidence is for sinusoidal oscillation.

TABLE 4 Types of "Disorientation" Reported by Armored Vehicle Operators

Disorientation

Topographic	Turned around
Navigation	Outside-in versus inside-out
North	Figure/ground
Maps	Vertigo
Heading	Apparent movement
Stakes	Dizzy
Homing	Lay gun wrong
Lost	Dizzy Sweat Vomit
∴ Bad performance	∴ Bad performance

In relative terms, there is some suggestion that perhaps 0.2 Hz is also nauseogenic for visual stimuli. So there is the potential for frequency-specific problems in the vehicle that could be bad.

We discussed disorientation earlier. I have two points to make about our use of words (Table 4). When we say "orientation" or "disorientation," we sometimes mean things like "topographic," "navigation," "where am I?," "where am I heading?," "can I follow the stakes?," "where did I just come from?," "am I lost?," all of which lead to bad performance.

The electronic displays lead us to be concerned about disorientation. However, this kind of disorientation may not be related to motion sickness. This kind of disorientation is characterized by such questions as: "which way is up?," "I now feel like I am upside down." "I have an outside in, inside out figure/ground problem which could result in vertigo." It may entail "apparent movement"; it may make me "dizzy." I may "lay the gun wrong," all of which lead to bad performance, the result of disorientation.

We have another semantic problem. Figure 3 illustrates an experiment that was made up (R. Kennedy, exempli gratia). The data are listed in Figure 3B, and the design is provided in Figure 3A. It is a simple manual control study. We are interested in what is the best system for the operator.

Manual control involves nothing new. The interests include the advantage of pursuit versus compensatory operations and different control

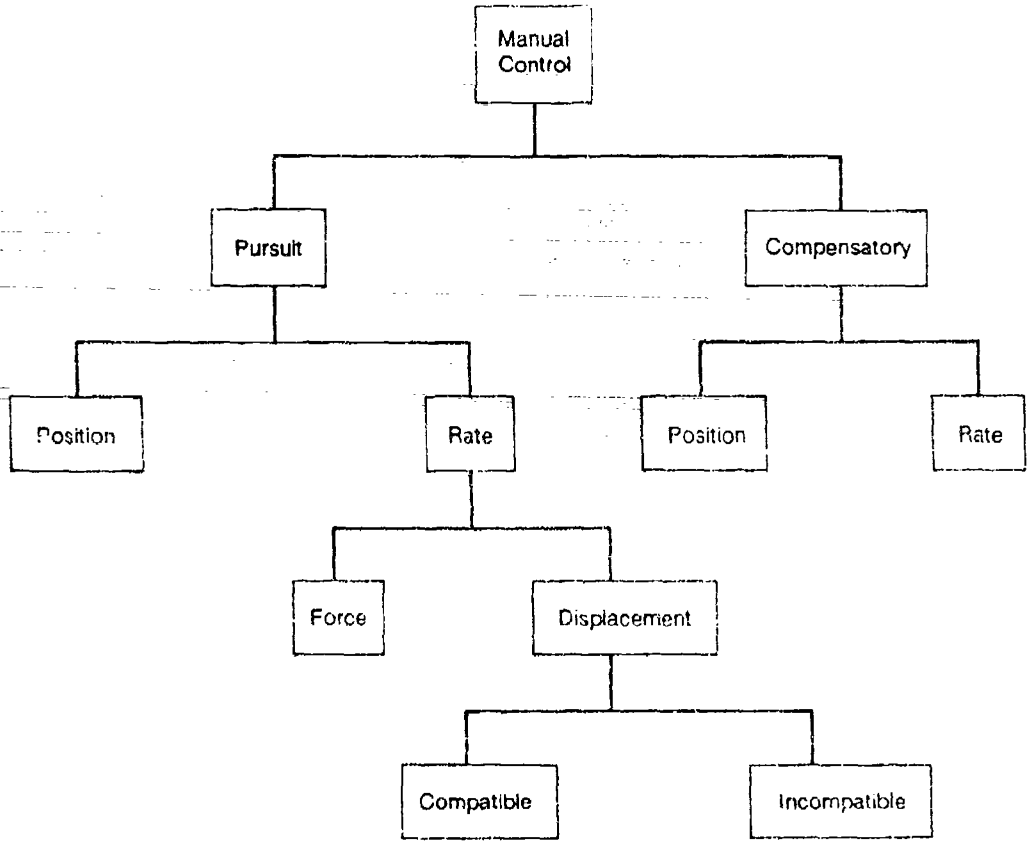


FIGURE 3 Design issues related to tactical system displays.

possibilities: position versus rate, the advantage of a force stick or a displacement stick, and the effects of a compatible versus an incompatible display.

If we were to do this multifactor (2×2×2×2×2 or 2^5) study with all the right procedures, the right number of subjects and with repeated measures, and so on, the data would look something like those illustrated in Figure 3B, in which arbitrary trials of practice and arbitrary RMS (root means square) errors are plotted. In general, over several trials we would get an error ratio that is less. However, only the differences in the second half are human factors engineering issues. If we were to do this study, we would find an advantage of pursuit tracking over compensatory control because one is fundamentally a better way of presenting information to humans. We would find that pursuit tracking offers an advantage over compensatory tracking when performance is asymptotic. Most of the other differences in this study would generally disappear with practice.

Even if this experiment did not turn out precisely the way I suggested, there are design criteria that represent fundamental ways that the human best extracts information from displays, and there are design criteria that achieve their utility by decreasing the amount of time it takes to learn to use the system. We often confuse those two points in discussing display design. For example, the difference between compatible and incompatible disappears with enough practice. People who have had all kinds of flips on their toasters, stoves, and wall switches have discovered that.

We need to separate the things that represent fundamental ways that the organism best uses information versus those things that involve a certain amount of training. We come to somewhat different conclusions if we keep those separate. Human factors engineering design criteria, which the military uses as standards, make no distinction between these issues. Some of the criteria represent modifiability and some do not. So the appeal here is for us to think about those criteria that represent fundamental differences in the way the person gains information versus those that represent modifiabilities.

Some suggestions about where we should go and what we should do about the occurrence of motion sickness in armored vehicles are listed in Table 5. Aaron Hyman's "tiger team" idea of people connected on a day-by-day basis is a good concept. There should be a simulator—perhaps several simulators—in which the kinds of systems that are being discussed can be tried out, driven around, moved around, and flown if they are air cushioned. There is an enormous problem surfacing with regard to wraparound displays. There are too few individuals in universities that do visual-vestibular interaction studies.

Anything that happens in universities will be 10 to 20 years behind the problem in terms of use of this new tank. But human factors of tanks are merely the tip of the iceberg. All future systems, not just military systems, but all future systems, are going to benefit from the research that we undertake today.

We should do surveys now for evidence of motion sickness in users of existing systems. We should go out and extract as much information from these individuals as we can. A survey needs to be performed with tanks and tank simulators. The survey should be conducted from the standpoint of the human operator and should include other devices such as flight simulators and remote manipulators.

Some management changes are needed in detailed specifications for systems when part of a request for proposal (RFPs) is not written properly from a human factor standpoint. There is a military standard in the offing from Aberdeen Proving Ground's Human Engineering Laboratory called

TABLE 5 Some Next Steps for Dealing With the Occurrence of Motion Sickness in New Armor Vehicles

- Hyman's tiger team concept
- Build a simulator/prototype
- Get universities interested
- Survey for sickness
  - Tanks
  - Tanks simulators
  - Other devices with tank-of-the-future characteristics
- Improve the way detailed specifications are written
  - Improve RFP's
  - Improve task analysis standard
- Exercise existing data bases
  - Naval Training Simulator Center, National Aeronautics and Space Administration, Brandeis University
- New methods for HFE
  - Linear system analysys for fidelity
  - Protocol analysis
  - Isoperformance

the task analysis standard. This is a step in the right direction although it is still imperfect. For example, the standard does not take into account what we know about vision and visual information processing or visual capabilities. They could be more specific. The standard refers to input parameters. It has four, including information required, information available, initiating cues, and data display format. High spatial frequency and contrast sensitivity (a specific form of visual acuity) are visual capabilities on which we know people differ markedly in the areas of identifiability and reliability. These are not mentioned in the standard, yet all of these things can influence performance. The task analysis standard says nothing about glare recovery as opposed to light sensitivity, color perception, or other things for which we know that people have markedly different capabilities. So the task analyses need to be improved in terms of the input parameters that are specified.

METHODOLOGICAL CONSIDERATIONS

To improve the design, furthermore, we need to exercise existing data bases. James Lackner of Brandeis University has over 100, the National Aeronautics and Space Administration (NASA) has over 2,000, and the Navy has another 2,000 cases of people who have been exposed to markedly different kinds of stimulation. Their responses or outputs may be similar to those that will be found in the tank of the future. There may be ways that we can use these existing data bases at the Naval Training Systems Center, NASA, and at the Life Science Center in Houston.

Linear Systems Analysis

There is a way to use linear systems analysis to identify fidelity. For instance, there was a study done in a simulator in Orlando, Florida, that has the capability of varying refresh rate, resolution, and luminance on the electronic display. In this study, people's high, medium, and low contrast sensitivities were measured. (There were only four subjects, so this is a "probe" in the best expression of that term.)

The equipment features of the simulator could be varied. What they found was that the contrast sensitivity of the subjects at the high spatial frequency was correlated with resolution. That is, the more resolution put in, the more important was the person's basic contrast sensitivity at the high spatial frequencies. The same thing happened but reversed, with the physical contrast conditions that were studied in the simulator.

Recall that we are only talking about four subjects, but these data can be used to suggest a way of doing an analysis. To answer the question "how much fidelity?" first you need to know what the basic substrate is that governs the performance. Then you raise the fidelity and you should observe an increase in the relationship between those who have more of that ability which supports the activity. The correlation should get higher as you increase the fidelity, up to a point. That point is the point of transition from being system-limited to being eye-limited. When the correlation no longer grows, you do not need any more physical fidelity. So this is an approach that has promise for establishing fidelity. The requirement is to know what the substrate is. To use this approach you must know what the behavior is that governs the performance.

Protocol Analysis

Ericsson and Simon (1980) suggest the use of protocol analysis as a way of conducting analyses for visual tasks. The assumption in protocol analysis is that if I tell you what I see as I see it, it is more likely to be what is getting into my central processor than if I tell you after I have seen it. People who have used this approach have conducted several laboratory studies. We tried it in a situation in which we had pilots fly an airplane and tell us what they were doing while they did it. The entire narrative was taped (see the appendix to this report). In another situation we had a former tank commander drive through the woods in order to do a task analysis of what the tank commander does. Let me state briefly what was reported:

> It is approximately 4:30 in the afternoon. Weather conditions are clear. The area is afternoon/evening dusk. First position is a gently rolling piece of terrain. The terrain would require careful travelers with covering fire, dangerous direction, right and left. Most of the heavily wooded area would probably not be attempted unless they were cleared, either by artillery or infantry force. Some of the long-range vistas would have to be traversed quite quickly with considerable covering from overwatching tanks.

The tank commander then talks about what he sees and he talks about what he sees in real time. We propose that such an approach could improve the way task analyses are performed. That it is a lengthy data reduction process, and a useful technique for doing task analysis.

Isoperformance Methodology

The last issue is isoperformance. Isoperformance offers a decision aid in the design and development of new systems. It suggests that the same level of performance can be obtained by different combinations of personnel, training, and equipment. Once the combination has been determined, a choice can be made in terms of maximum feasibility or minimum cost. It allows the operational commander to identify the level of desired performance.

For example, the commander of the air group says "I must have an 80 percent boarding rate. Otherwise, I do not want to go to sea." The fellow who runs the steam table in the food service section says, "You have to be able to dollop 20 scoops of mashed potatoes a minute to be able to operate at this steam table." The squadron commander wants a person to be able to pull a radio from an F-4 in 4 hours and bench test it or to complete a 50-mile forced march with a 30-pound pack in 8 hours. Those are examples of operational criteria.

If operational people can specify a level of performance that they want, then isoperformance can be used within systems engineering. It may not be cost-effective to design a system based solely on the engineering issues or the equipment features. It is far better to talk about the possibilities.

MANPRINT is another emerging initiative within the Department of Defense. Training is important both in terms of design as well as in terms of fitting people to the system. For instance, there are some people who can have an 80 percent boarding rate on the first day of training. If all you had to do was pick those people, you do not need a training program. On the other hand, there are some people who, even if you give them the best display, are still only going to be able to achieve this kind of performance with very expensive training; there are costs associated with selection, and there are costs associated with equipment.

The problem is that too often we attempt to design a military system based only on the equipment issues. The people who want to select personnel are not talking to the system designers. The prospect of making those trade-offs should be considered throughout the entire design process.

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Correlation and Decorrelation Between Visual Displays and Motor Output

RICHARD HELD

A recent conference at Asilomar (Ellis, 1989) led me to consider many of the issues being addressed by this working group, issues having to do with interactive displays. Together with Nathaniel Durlach, I wrote a paper for that conference called "Telepresence, Time Delay, and Adaptation." Our concern was with the interaction of the whole person with displays—a typical human factors problem looked at from the point of view of a psychologist and an engineer.

Figure 1 was produced in the last century by Ernst Mach, whom many of you may know from other connections. I think you can all see what it is. Mach has one of these Austro-Hungarian mustaches. The illustration is addressed to the issue of viewing one's own effectors, or more generally, one's own body parts, and it is of some historical interest. He is looking out of his own orbit through one eye into space. You see his body stretched out in front of him. The point is that here he is on site, observing himself under perfectly normal circumstances. He is holding a pen or whatever it is in it, and if he moves it, he knows he is moving it. It is the basic situation that we find ourselves in most of the time.

VISUAL-MOTOR TRANSFORMS

Let's contrast that situation with the decorrelation between motor output and visual displays. Suppose you pick up a hammer and instead of having your hand out here, you in effect extend it a foot or so. You put a very simple transform into that loop (Figure 2). You almost instantaneously know how to use it, although if you watch a child, it does take a little bit of learning.

One can put a more complex transform into the loop. How many of you know this game called Etch-a-Sketch? It takes a long time before you really get any control. For those of you do not know it, x displacement is

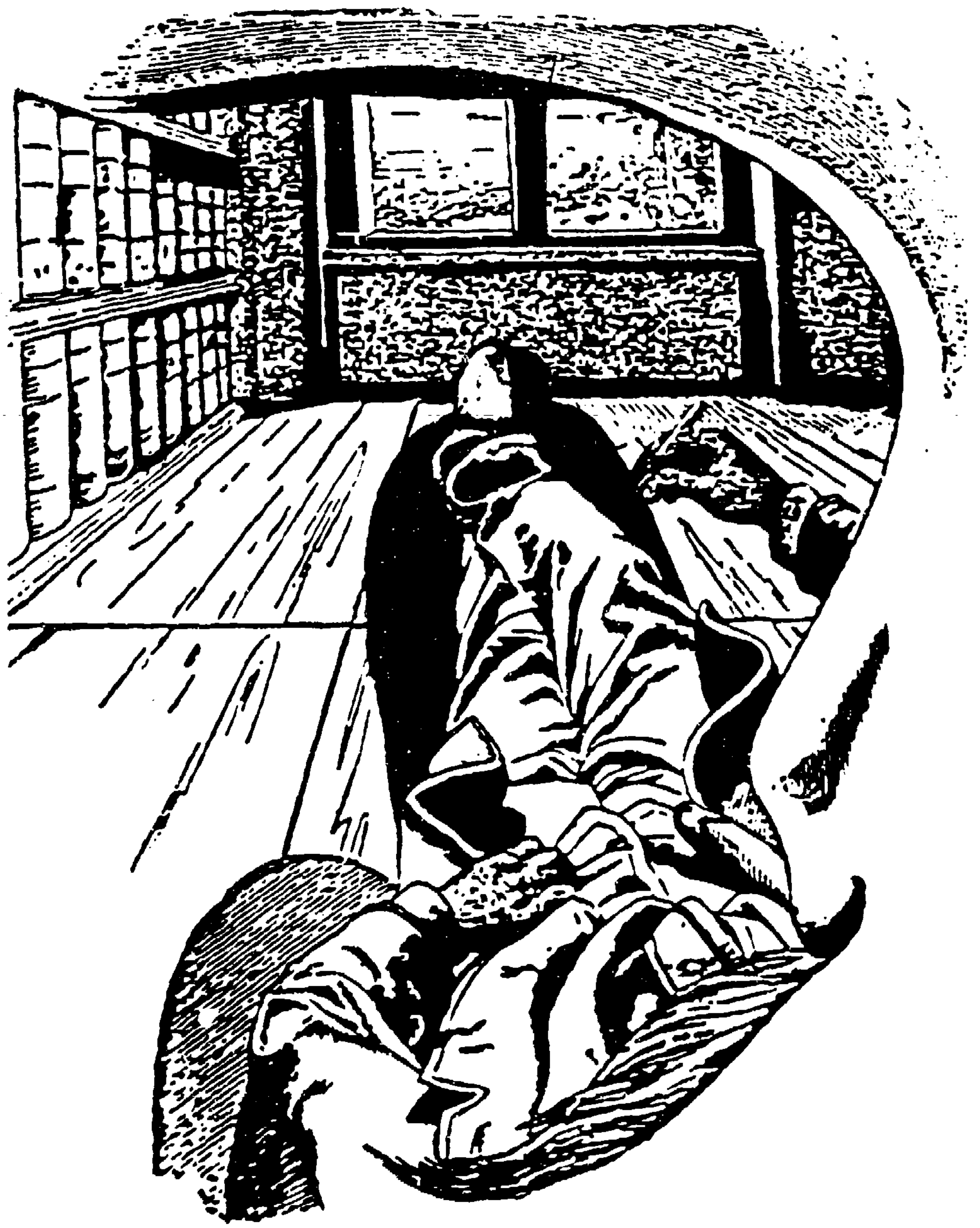

FIGURE 1 Viewing one's view of the world. Adapted from Mach (1914).

produced by rotation of the right hand, y displacement by rotation of the left hand. It is a transform that takes a lot of time to get around before you can use it.

Both of these transforms now are transforms of the output end. But you all know you can just as readily transform the input end. Typically, some of us have played around with distorting eyeglasses and prisms and

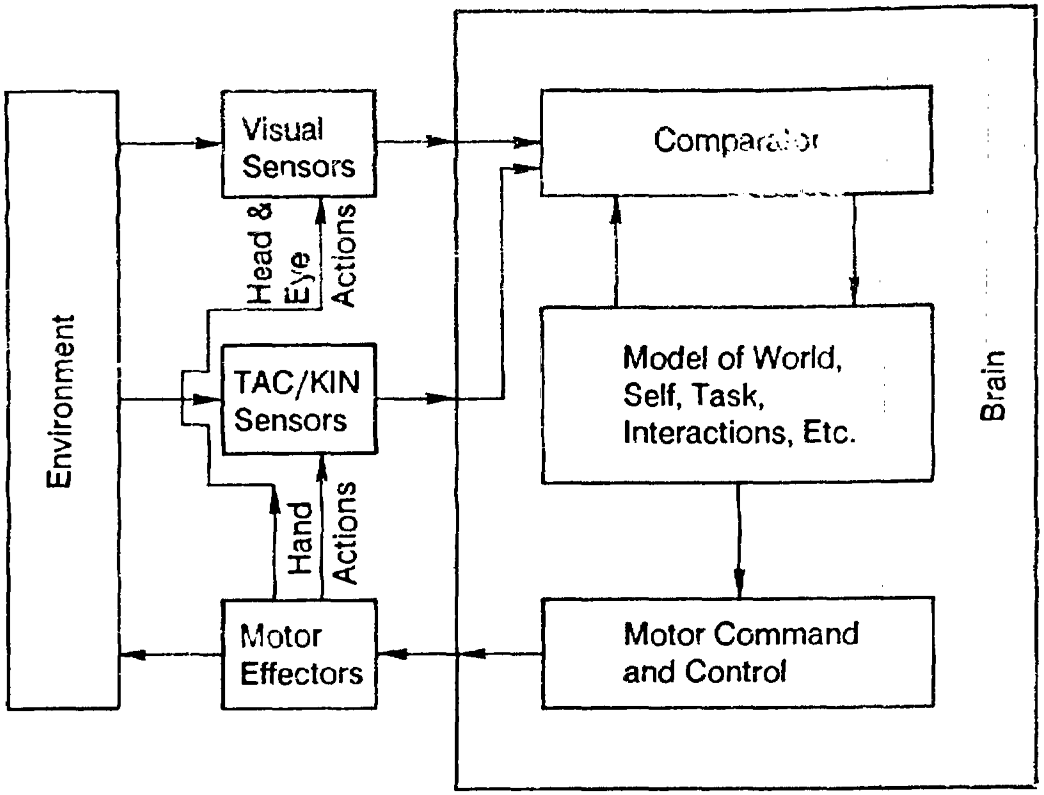

FIGURE 2 Transformations in visual output/motor input loop.

have studied the adaptive effects of those things. So you can put transforms on either end of the system, and as everybody knows, we can make a general rule: the more complex a transform you put in the loop, the more time it takes to adapt or to learn how to use it. This is equally true whether one is handling vehicles or handling tools. When you put a complex transform into the feedback loop—and the more that transform deviates from the normal conditions exemplified by the Mach illustration—the more initial problem you have. I would also hazard a guess that the more radical a transform is, the more provocative it is as far as getting motion or space sickness also. It takes more time to adapt.

TELEOPERATIONS

If you apply these findings to the problem of teleoperation (Figure 3), you of course entail transforms, both on the output and the input ends. Everybody is probably familiar with this concept. It says that if you have a teleoperator system and a human operator, you can monitor output with some sort of response sensor system. Effectors at a remote position—the so-called slave robot—then act on the environment. The robot may provide tactile or kinesthetic feedback by itself, either through the environment or directly if you are monitoring the output of mechanical arms, say, with a tactile system. You can also get visual and auditory feedback. You bring those signals back to the teleoperator station, and you transduce them, by some sort of visual or tactile display, back to the human operator. The human operator, of course, has direct feedback as well of his own motor activities.

The problem with teleoperation is: how do you maximize the efficiency of a teleoperator system? One way that our colleagues from human factors research tell us to do that is to maximize what they call telepresence. Telepresence is essentially trying to minimize the transformations that you have in a system of that kind. You want to minimize the learning time, the adaptation time, and so forth. You want to maximize the ability of the operator of such a system to use normal sensory and motor strategies. You want to minimize transformations. Of course, you run into a trade-off between the cost of state-of-the-art technology and the minimization of transforms.

We still have these feedback loops whether the operator is in a teleoperator system or not. We know very well that the oculomotor system has a storage process that models the chronic state of interaction in this feedback loop. This stored model derives from the orderly relation between movement and feedback.

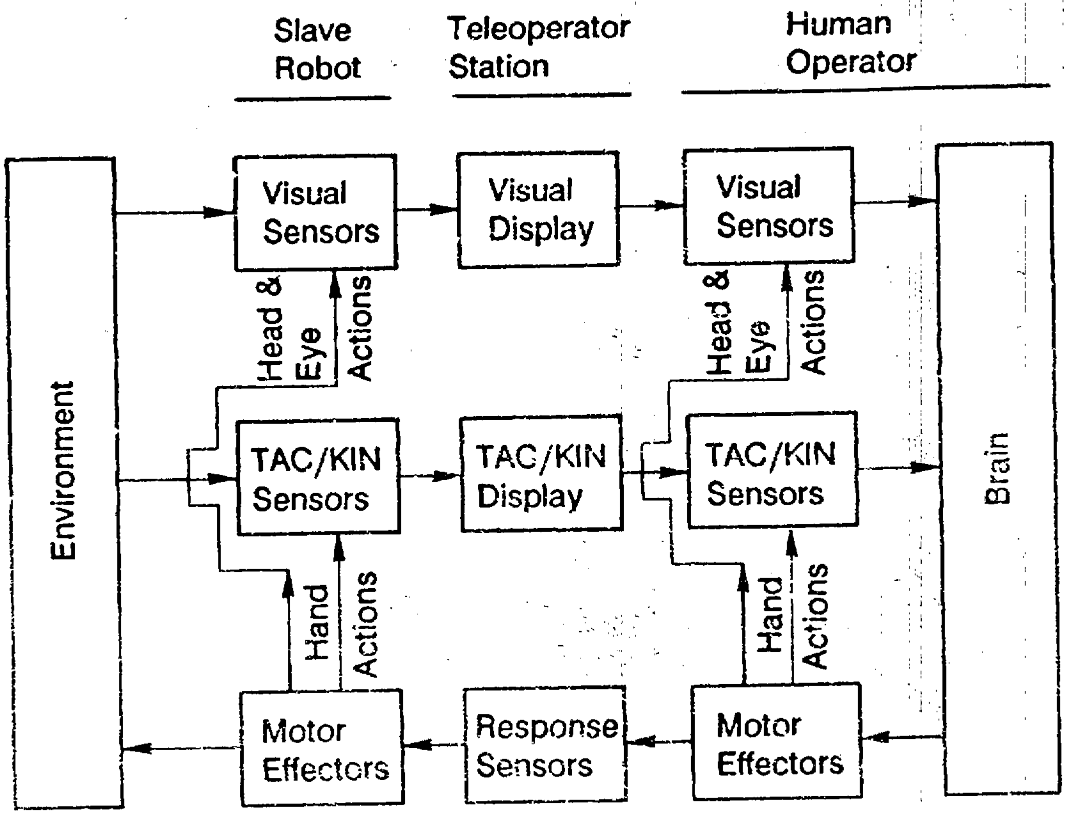

FIGURE 3 Visual-motor transformations in teleoperations.

If you get an error signal, just as Sheldon Ebenholtz described (elsewhere in this volume), you can update the model of the world. That can occur in teleoperator systems and in experiments in which you produce a transform in the loop. Telepresence itself appears to be modulable by learning and adaptation. You apparently can alter or transform that sense of telepresence, as well as the abilities that go with it, by such exposure.

I think the most interesting aspect of this research—and this comes back to a question Robert Kennedy raised elsewhere in this volume—is how many parameters in the feedback loop are determined to the habitual state of interaction with the world, and how many are simply inherent in the way the human brain processes information?

That is something that I think one has to decide by experience. But we can make some educated guesses about how a strong telepresence is established and how it can be maintained. On the sensory end, high resolution is important for some purposes. A large field of view and consistency across the modalities will also be important. If you have intersensory discordants, as it has been called, you have a problem of learning or adaptation. You want to get a large range of sensory-motor interactions. You want the movements of sensory organs to be produced by output from the operator.

FACTORS THAT DEGRADE TELEPRESENCE

The correlation between sensed movements and displayed feedback information is very critical. We can ask: What are those conditions that really degrade telepresence and ultimately may preclude adaptation or learning?

Three sorts of conditions seem to do that. One is time delays—even of a short time. It appears that anything over 200 milliseconds clearly degrades telepresence. A second, noise, is always deleterious and it is always there. Noninvertible distortions, such as light scatter, and very complex transformations degrade telepresence and probably yield conditions to which operators cannot be adapted. Finally, learning and adaptation enhance the sense of telepresence.

Telepresence is a useful notion, but it is essentially not a deep notion. We need to find out what, in fact, are the conditions that will promote the ability to use the capabilities that the operator comes with or can adapt to most readily.

There is also another approach to this problem. If you think back to the picture by Ernst Mach (Figure 1), that is the condition under which we feel we are present in our environments, that we are on site—that it is we who are operating on the world. How can that experience be degraded? If we know how, we can degrade it; we will also know how it is created. This procedure may be an interesting approach.

APPLICATIONS IN ARMORED VEHICLES

The lesson with regard to the problem of the tank is that we must try and find out what the unavoidable degradations of telepresence are. If you are going to have a visual display system inside a tank, you are going to have inevitable delays and noise. You may have noninvertible distortions, but you want to find out how big they are and how tolerable they are, for obvious reasons.

Another implication of what I said is that we need to do research on what sort of time delays are tolerable, and what the effects of these perturbing conditions are on adaptation. Let me tell you about the results of a time delay experiment.

The time delay experiment followed upon an old experiment that we did a long time ago; it derives from the original experiment done by Helmholtz in the nineteenth century.

If you look through a prism, anything you look at will look displaced. Consider a visible target, for example; you are going to see it in a particular place. If you reach for it, you reach with an error. However, Helmholtz showed that if you watch your hand through the prism for a while, you adapt and you start to reach more correctly. If you then take the prism away and reach quickly, you are going to show the opposite error. You change your model of eye-hand interaction in such a way as to adapt for this transform in the loop. This has been demonstrated.

The question we asked here is: Suppose we introduce a delay into the loop of feedback changes in hand position? We did that at first with a device that Tom Sheridan lent us. His laboratory was concerned with transmission delays on the order of 250 to 300 milliseconds—transmission to the Moon and back. We set up the system in such a way that the subject marked the image of a virtual target (Figure 4), so we got a measure of the accuracy of initial and postexposure marking. During exposure, the subject then moves a cursor, which in turn drives a spot on a cathode ray tube, which the experimenter could both displace and delay. The subject watches the spot as his hand drives it. It could be driven in synchrony with the hand or with a delay.

The kind of data we got initially showed the course of adaptation during periods ranging up to 30 minutes. This long period of exposure can be excruciating, but nothing compared with the experience of a tank

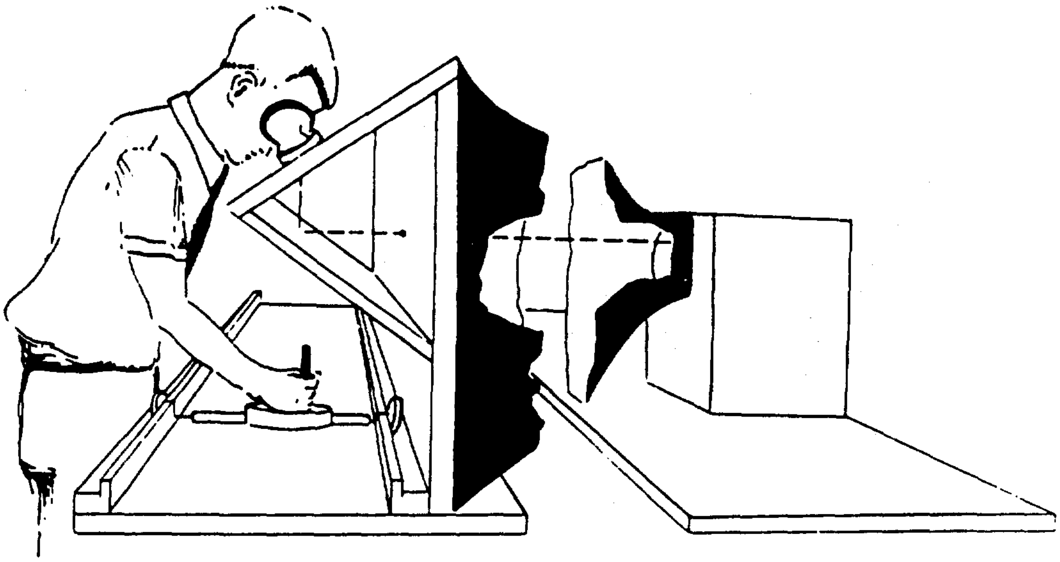

FIGURE 4 **Experimental apparatus for a displacement/delay experiment.**

operator. The induced delays ranged from 300 milliseconds up to 3 seconds. What we found was that essentially all adaptation was eliminated, even with a delay as small as 300 milliseconds. The subject would not adapt in this experiment with continuous movement of the hand viewed under delay. The results do not allow us to conclude that you could not get adaptation under other conditions with delay. That remains an interesting question.

Obviously, we needed to go to shorter delays. We did experiment with the outcome shown in Figure 5. First, I should say that for some reason there seemed to be some sort of asymptotic nonzero adaptive level. The main point, though, is that adaptation under normal circumstances of viewing steadily dropped from the zero delay condition down to the 330-millisecond delay. By 120 milliseconds you see a significant drop in adaptation.

If you watch the stimulus as you move your hand, up to about 100 milliseconds of delay, you see a slight lag. It is as if you are pushing your hand thorough a viscous medium. After that, you definitely notice a delay. If you are moving your hand at random and rapidly as that delay increases, the feedback you get appears to be dissociated from the hand movements.

The interesting question here I think concerns the conditions under which the spot is identified with the hand—visual feedback with the output of the brain, so to speak. That must be the condition that can lead to adaptation over and above the existence of a displacement. It might also be one criterion for the sense of telepresence. That is, you identify the movements of the hand with the spot that moves in concordance with those movements, and not otherwise.

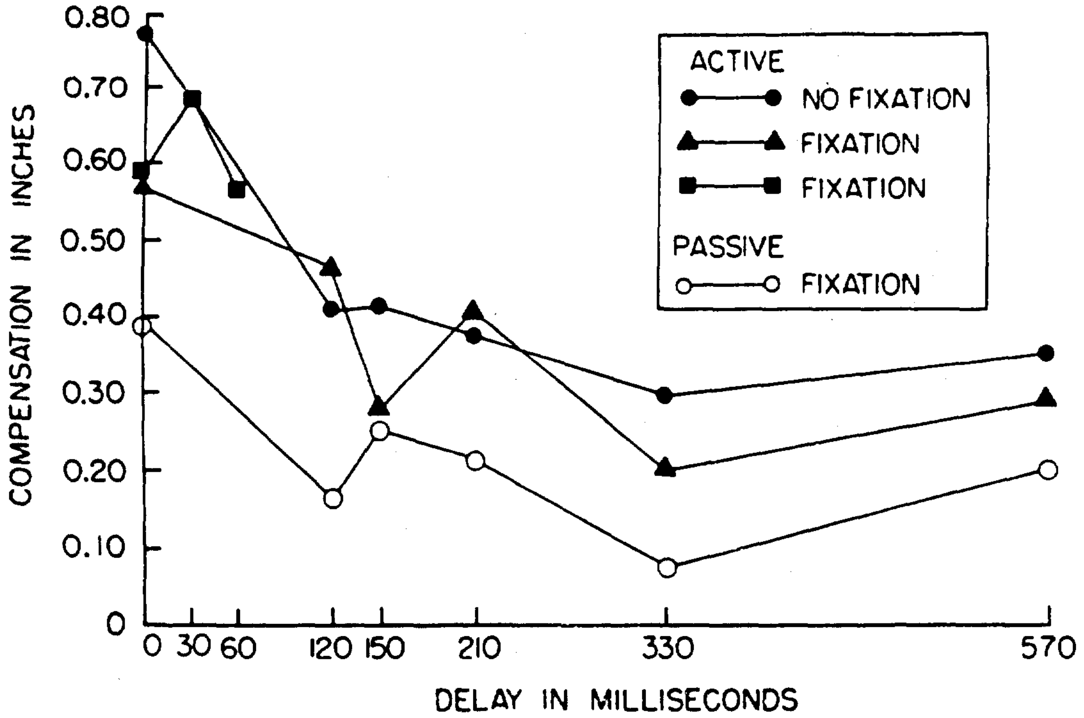

FIGURE 5 Adaptation response in displacement/delay experiments involving eye-hand coordination.

So, at least one approach to this question of the degrading effects of time delay can lead to a whole research project, and I think it should.

DISCUSSION

DR. KENNEDY: Would you want to add asynchronies? The reason I bring that up is that it makes a difference in simulators.

DR. HELD: What do you mean by asynchronies?

DR. KENNEDY: Well, in the case of simulators, there are asynchronies between the inertial and the visual stimuli. In the tank electronic display, there may be asynchronies between displays and real-time tracking.

DR. HELD: Yes, such phase lags are tantamount to time delays.

DR. LACKNER: These data are extremely interesting. If you look at the same range of values with delayed auditory feedback with a person hearing his own voice delayed, breakdowns occur at just about the same point, and then they continue up very much in the same fashion.

Some years ago we looked at adaptation to delayed auditory feedback. We found that people adapted reasonably well up to about a 100- to a 125-millisecond delay. Their performance also improved at 200 milliseconds and its multiples. This occurred only because they adopted certain strategies, such as blurting out the speech. In other words, they would not pay attention to what they were saying.

DR. HELD: We know there are definite strategies being used by the subjects.

DR. LACKNER: There was no adaptation in the sense of it being less cognitively constructed.

DR. HELD: That raises an interesting question on this end, because we know from Sheridan and Ferrell's work (1963) that the way to get around a time delay is to stop and wait for the termination of each discrete movement. That is done in visual tracking at a cost, because for every movement, we must add the delay time. You extend the time that it takes to do something.

Maybe if you adapt a stop-and-wait strategy in this situation, you are going to get adaptation. We have not worked with that yet. Our experiment involved a continuous movement. Therefore, the subject maximized the asynchrony in positions. There are many questions that we must answer.

DR. WHITCOMB: When delayed speech first came out, I never did have much trouble with it because I transferred my attention from monitoring the sound of my voice to monitoring my vocal musculature.

DR. HELD: You disregarded the hearing.

DR. WHITCOMB: Yes, totally. In your case it may be that, if the person concentrated entirely on their response, they can block out the vision.

DR. HELD: Well, I remember in delayed hearing you could recite a well-memorized poem without any trouble by simply disregarding the feedback in your ears. But try to compose a new sentence and you were in trouble.

DR. EBENHOLTZ: There may be some exceptions to the proposition that the more complicated the transform, the more difficult the process. Consider the possibility of independent channels or parallel processing. There was a study that conjoined displacement prism and tilting in which the evidence yielded virtually complete independence. So there are some limiting conditions. We must specify channel capacity and the numbers of channels.

DR. HELD: I agree, absolutely. We do not know what more complicated transform means.

DR. LEIBOWITZ: Where does the term telepresence come from?

DR. HELD: It comes out of the teleoperator mythology.

DR. KENNEDY: I think that telepresence must be delineated as a design goal. I believe that there is an urge on the part of engineers to be given counsel or receive counsel if they can make it look like what it is. If they can make it feel like what it is, there will be zero training, and that is not necessarily true.

DR. LACKNER: This reminds me of an observation we made several years ago. We were looking at the situation involving active versus passive tracking in total darkness. The curve resembled this curve, but it was markedly lower.

DR. HELD: The passive-active dimension—somebody will tell us what that means.

DR. LEIBOWITZ: Jim [Dr. Walbert], to what extent is delay a problem in tank operations?

DR. WALBERT: Well, there is a serious delay problem. It is well known in normal tracking exercises, especially for crossing targets. One of the standards is a circle. The target tank is moving in a circle, and the gunner is required to track the target. The turret is rotating. Moving the gun right to left is a matter of taking vertical movement of the handles—so already we have the kind of transformation that Dr. Held is talking about. An attempt is made to move quickly onto the target. Because there is a circle delay in moving the gun, however, you have gone too far, and then you try to correct too quickly and you go back too far. This involves a manual or servo decay.

DR. KENNEDY: Are you familiar with the Rutschaan and Link paradigm?

DR. HELD: No.

DR. KENNEDY: Well, results from the Rutschaan and Link paradigm imply that when the simple visual reaction time is 180 milliseconds, the simple auditory reaction time is 160 milliseconds. However, for me to identify when a visual and an auditory signal will occur simultaneously, I must lead the slower channel with the faster channel. Aside from the paradoxical result, this outcome underscores the fact that the determination of simultaneity is a difference judgment in the brain from simple detection of each of the stimuli. So when I have laid my gun on the target from the standpoint of muscles and joints versus vision versus auditory signal, it may not be the same point in time.

DR. EBENHOLTZ: Apropos of position and velocity, the eye movement system has both. You have pursuit and saccadic motion. Saccadic motion is based on position; pursuit is based on velocity. Is it conceivable that one could use both of these in gun laying?

DR. WALBERT: I suppose there is a combination of both. When we try to collect data with civilian gunners at the Aberdeen Proving Ground, these people know the terrain so well that they know when a bump is coming up and so they do not fire. After the bump is over and the oscillations have settled down, they fire. We do not get good data on the performance levels of the system because the system is never used at its performance levels.

In a true cross-country shoot, the chances are that the gunner has never been across that course before. That is when we get some sense of performance levels. In a true test, it is more likely that the gun will be fired when it is moving down than when it is moving up. There actually is a difference in doctrine training between the Army and Marine Corps for whether you bring a hand-held weapon down or up to fire. The Marine Corps says you bring it up and you bring it up slowly. That is their current doctrine, mainly to take advantage of the recoil of the weapon.

In tank gunnery, more often than not, the weapon is fired when the gun sight is coming down. Whether that is optimal to the system or not, I do not know. There is clearly a connection made between the position of the gun and the position of the target.

DR. HELD: In regard to the delay experiment, we know that resolution varies from scale to scale. It is conceivable that one might find that these different spatial frequencies exhibit different delay tolerances. One might be able to spatially filter a display when delay is an inherent component.

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Lessons from Simulator Sickness Studies

HAROLD VAN COTT

When faced with a system design problem, the first thing I typically do is identify the task required of the personnel in that system. If I know what these tasks are, then the information and response requirement of the tasks can be used to specify the characteristics of the displays and controls needed to perform them. In the case of a future Army tank, I reasoned that if I could identify the information requirements of the crew, I could say something meaningful about the displays they would have to have; and if I knew what these displays would be like, then others specialized in motion sickness could indicate which display characteristics might be associated with motion sickness and which would not. In this manner it would be possible to answer questions related to the desirability of using a wraparound electronic display in a tank.

I obtained a task analysis from the U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, for the M-1A-1 tank. Even though we are considering a future tank with different characteristics and a smaller crew than the M-1A-1, I assumed we might be able to say something about information and information display for those tasks in a future tank that are the same as those in today's tank. Unfortunately, the task analysis available to me contained insufficient task information to identify crew information and display requirements. Recognizing that I took an alternative tack, I decided to examine the display characteristics that research demonstrates induce motion sickness. My source was a report, *Research Issues in Simulator Sickness*, issued by the National Research Council's Committee on Human Factors in 1984. My reading of this report suggested that it might contain information that could form the basis for developing some guidelines for future tank displays that would minimize display-induced motion sickness.

Five of the people who were involved in the development of that 1984 simulator sickness report are here today. Since I have no special background in motion sickness, I hope they will elaborate on my remarks and correct my omissions and errors of interpretation.

Research Issues in Simulator Sickness dealt with motion sickness in aircraft and automobile simulators. Both of these types of simulators have properties that might be expected to occur in a tank with a wraparound display—the physical motion of a platform, a large display screen surface, and extensive and rapidly changing information.

Simulator sickness, of course, is experienced by users of both fixed-based and motion-based flight and automobile simulators. It occurs during the use of a simulator and for a good many hours afterward. Reports vary from 10 percent incidence in the 2F112 simulator to 88 percent in the SAAC simulator. Both of these are fixed-base simulators. The symptoms experienced are familiar: nausea, vertigo, discomfort, dizziness, leans, disorientation, vomiting, and so on.

SIMULATOR AND USER CHARACTERISTICS

A large number of simulator and user characteristics appear to play a role in inducing simulator sickness. Some with the greatest apparent relevance to the tank of the future include the following:

- motion and vibration (axes, frequency, acceleration, exposure duration, lags, phase/gain),
- vision (field of view, framing effect, retinal eccentricity, off-axis display, scene features such as number and appearance),
- display type (computer-generated imagery, point source, model board),
- pilot head movement,
- visual motion (lags, phase/gain, optometric properties, spatial frequency, raster scan, phosphoresis, refresh rate, etc.), and
- pilot characteristics (medical condition, duration of exposure, prior training and experience).

RESEARCH FINDINGS

Sensory conflict theory is the most common explanation for simulator sickness. It postulates that sickness arises from a referencing function in which motion information from vision, the vestibular system, and proprioceptors may be in conflict with the expected values of these inputs derived from past experience. However, the theory is not sufficiently advanced to permit predictions to be made about the degree of sensory conflict that can occur in any given dynamic situation based on a set of design and other input variables.

Some of the lessons learned from this report on simulator sickness appear to have application to the design of future tanks. Cases of simulator sickness have been documented with computer-generated imagery and point source lighting systems but less frequently with model board systems. One of the most important variables in producing simulator sickness is the size of the field of view of the visual display system. In general, a wider field of view is associated with a greater likelihood of sickness.

A wide field of view provides more stimulation, resulting in a more compelling visual display of motion. This enhanced sense of visual motion may contribute to conflict with vestibular inputs. The SAAC simulator has a mosaic of eight electronic screens that surround the canopy of an F-4 cockpit and give a 296-degree by 80-degree field of view. Reports suggest that disorientation and other symptoms occur with this full eight-window display but not when three mosaic screens are used.

Scene detail is another important variable. Greater scene detail provides the visual system with more information about spatial dynamics, presumably sharpening the perception of motion and generating greater conflict with vestibular inputs.

In some training simulators, video images are written in different directions on adjacent windows. This may create an unusual visual stimulus of simultaneous movement in different directions that could contribute to motion sickness. The same problem of multidirection video writing is likely to occur in new simulator displays in which an exploded area of interest is displayed within a larger area, their imagery being written in different directions.

Optical distortions have often been mentioned as contributors to simulator sickness, as have poor resolution, flicker, and off-access viewing.

Research shows that whole-body motion at a frequency of 0.2 Hz is most distressing to a simulator user and should be avoided in some way. If three-dimensional visual displays are introduced in the future, motion perception, perceptual adaptation, and after-effects may become even more important than they are with conventional two-dimensional displays.

Research generally indicates that exposure duration also contributes to motion sickness. Limiting exposure duration can provide temporary relief from symptom buildup. The implication of this finding for tank design is the possibility of a display call-up capability that can be exercised at the option of the crew only when the demands of tasks require that certain scenic or other information should be made available.

In simulators, large rapid head movements during angular motion of a simulator can cause vestibular coriolis effects, while head movements during visually represented angular motion can cause pseudo coriolis effects. Both of these, of course, are associated with motion sickness. The implications for tank displays are to design the display system to minimize the need for large head movements in scanning the display surface.

These lessons all point to guidelines for the research and development that would seem to be necessary to create an effective wraparound display. One of the prerequisites is the need for information on task requirements and the visual inputs associated with them.

SUMMARY

In summary, the following guidelines are suggested in *Research Issues in Simulator Sickness*. The field of view of the tank display should be no wider than necessary to present the information needed to perform the tasks. Separate display screens for individual crew members are preferable to a shared, single common display screen because of the reduction in screen size that is possible with individual screens.

If video imagery is used, it should be written in the same direction on all the display surfaces, and distortion should be avoided. The necessity for images to be displayed in the periphery of vision should be avoided if possible. To minimize the need for head movements, controls should be located in the frontal plane of the body rather than to either side. Tank motions that induce 0.2 Hz of body motion should be minimized through vehicle suspension and design.

The possibility of a call-up display should be explored so that there is not a continuous presentation of changing information. The number of stimuli used to represent the real world should be no greater than necessary to support task performance requirements. In this regard, I think there is a trade-off between realism in a visual display versus only those features and details that an individual must have to make the discrimination and perceptions and decisions needed for tank performance.

Those are the findings in the report. What has happened since 1984 in the way of design-oriented lessons for the tank display system that we are talking about?

DISCUSSION

DR. KENNEDY: There are some ways to predict who is going to get sick from the wraparound tank system if motion sickness becomes a problem. There is a good factor analysis of the symptomatology now, so that there is a three-factor solution in addition to a general factor that appears to indicate that there are eyestrain-type problems, visual-vestibular-type problems—which were somewhat disparate—and there are neuro-vegetative symptoms that are factorially different, that is, that may reside in different kinds of simulators.

Postural equilibrium is significantly affected following exposure in a simulator. This implies that there are changes to individuals, so that riding in simulators may have some influence on their ability to conduct other activities when they leave, for example, driving home. These changes may carry over into tanks or other systems that use similar kinds of displays and are definitely related to the proposed wraparound system. People are immune, or appear to be immune, even under the worst "known to be poorly designed" situations. Thus, a study of these kinds of individuals may provide some important counsel.

DR. VAN COTT: Is there transfer of adaptation from prior experience to a simulator, for example, if an individual has been a truck driver or a pilot?

DR. KENNEDY: There probably is transfer, but those things are poorly understood. The data emerge from slightly more than a dozen situations. There is one set of data from an Army attack helicopter simulator where the individuals had very nice learning curves from the standpoint of symptomatology reduction over successive "hops." That is, with each simulator successive "hop," there was a decrease in the symptomatology that persisted over the course of their training.

On the other hand, there was an increase in postural disequilibrium, which also followed the same course. The postural disequilibrium measured after a person came out of a simulator increased over sessions, which is perfectly understandable, based on the fact that pilots adapt to this simulator world. It also means they must recalibrate when they get out, and must do so more each time. Therefore, there is a postadaptation phenomenon that gets bigger and bigger over trials, which may mean that they are becoming increasingly at risk if there is an implication that that sort of effect transfers to driving or roof repair. The same central nervous system mechanisms that govern walking and standing are used in driving and steering—which is why the police use standing steadiness as a measure of your ability to navigate.

DR. HYMAN: What was it measuring?

DR. KENNEDY: The abbreviated floor walking and standing test? The better data are for standing, and are less good for walking because there was a ceiling on the walking test scores—a range restriction. It is nothing that one would like to do in a laboratory. However, I would like to point out a potential measurement tool that the Army may already own.

The helicopter simulator uses a night visual system that is presently usable in the simulator. It entails the use of a hard hat that is fitted carefully to the head. It accurately measures head position for the purpose of guiding the weapon system's bore sight. When the operator gets in the helicopter, he plugs into the simulator and locks himself in. I highly recommend this, in terms of a device that might be usable (if similar systems are envisioned for a tank), when the Army puts out the request for proposal for a system. They also have one specified for use by the operator for experimental and adaptation purposes. When a pilot gets out of the simulator, he plugs into the same type of connector, which measures his ability to stand steady by again measuring his head position. This would be locked into sensors in the overhead, and one could ensure that he was standing steady.

DR. VAN COTT: You answered the question of what is new. Do you want to elaborate on these studies that you have done on the use of vection as a predictor for motion sickness?

DR. KENNEDY: The stimulus conditions using a vection stimulus included a helicopter slalom course on what is called a low-cost test bed. The operators were passively flown through at 140 miles per hour at less than 500 feet on a slalom course presented on a wide field of display. I do not remember the dimensions but they were about 160 degrees horizontal and about 40 degrees vertical. Of those subjects who reported vection, some got sick and some did not. Of those subjects who did not report vection, none got sick.

Whether vection is a sine qua non for simulator sickness or not is problematic, but it seems to be a very important ingredient.

DR. HYMAN: I was going to make an observation about the location of controls. We have been addressing displays in vehicles that we assume are relatively slow moving, with relatively reduced magnitudes of acceleration, so that some of these spatial orientation and other effects such as nausea are not going to arise from movement of the vehicle. They are more likely to occur because of disparity between the display and the type of vestibular input. But, if we put a man in a turret and the turret rotates at a fairly rapid rate (if he has to look down to see what he is doing with his hands, and the turret is spinning) we have the characteristic situation of what we experienced in the rotating room. If this working group meets again, it would be helpful to expand the discussion to include the requirements for controls.

DR. KENNEDY: Three rpm (18 radiuses per minute) or less is slow. I think that the air-cushioned vehicles are going to turn a whole lot faster than track vehicles, if anything, so it is not just turrets. It can be greater than 3 rpms. Whether it does that operationally or not and for what period of time, we do not know. As far as the forward motion of the tank is concerned, tanks are capable of traveling at 60 miles per hour. The M-1A-1, the Marine Corps light armored vehicle, can travel at 60 to 70 miles per hour on the road. That is a wheeled vehicle. So in terms of driving, most of these vehicles that we are talking about—and we are talking about something in the future—will be lighter in weight than the M-1A-1. Therefore, they should be capable of high rates of speed. The driver, therefore, must respond and needs the same sort of response he would for driving an automobile.

In regard to target acquisition and tracking, I do not envision a vehicle firing on the move at those speeds. I would cut the speed in half as a top level. Certainly, you would not want to shoot while traveling at 30 miles an hour in the M-1A-1.

DR. HYMAN: We have not addressed computer-aided aspects of displays. We also have not addressed the response times that will be needed in future systems. If you have a situation where the gunner's task is no longer tracking the target, then even though it is computer-aided, the gunner still must put the reticle on the target and keep it on the target as it is moving. The computer picks up the transverse rate of the target across the frontal plane. In the future, it might be that the gunner just has to get into the target area, and the logic of the system will be such that it will define what the target is and where its vulnerable point is. All the gunner will do is make the decision of go/no go for releasing the munitions. We have not addressed the kind of display that retains that kind of role for the gunner.

Another thing that has not been addressed is constraint of the body in rapidly moving vehicles. A tank operator can be slapped around in a tank, and can come out of it badly bruised. It is not a matter of pampering the military. It is a matter of keeping them fit so that they can fight. So if you are concerned with fightability, you might want to deal with cushion-constrained working environments and—to make it even more difficult—in a buttoned-up situation. How long can a man operate in a ground vehicle in a constrained position? Do you expect the man to be functioning for 6 hours without really being able to move freely?

In a distributed battlefield, where the commander is isolated, instead of having a staff on board his vehicle, he has to learn to view the world through a display. The display content becomes critical. How do you substitute for the kind of rapport that he needs with the generators of the information?

DR. KENNEDY: The point that Aaron Hyman raised about restraint systems prompts me to ask the question: What is known about the relationship between simulator and other kinds of motion sickness and the use of restraint systems?

DR. VAN COTT: That is a tough one. Restraint systems probably help, but I do not know of any good data. Anything that will help you regularize the stimulation of the end organs is likely to help.

DR. HYMAN: So one benefits by being stabilized with a restraint system in the tank that bounces around.

DR. KENNEDY: What is the incidence of vertebral fracture in tanks?

DR. WALBERT: I have no idea.

DR. KENNEDY: You must have some *g*-recordings. You must get up above 0.5 *g* or more routinely.

DR. WALBERT: There are profiles available from Warren, Michigan. They use the same accelerator readings on the shake table. They can generate any of the Aberdeen Proving Ground courses right on that table. It is all recorded on tape.

DR. LEIBOWITZ: From what I understand, pushing is not what you want to do to avoid impact injuries.

DR. WALBERT: We were told—and I only had a 2-week course in tank training because that was not my field in the Army—to try to hold ourselves firmly in position; otherwise, we would end up on the opposite side of the vehicle. That was not the M-1. The M-1 is a very smooth-riding tank compared with the M-60, its predecessor. They have done a lot of work on the suspension system.

DR. LEIBOWITZ: What is the dominant frequency at 30 miles per hour on country roads? About 5 Hz?

DR. WALBERT: I am less familiar with the suspension than I am with the fire control system. The fire control system and the stabilization system have a bandwidth of 5 Hz at a good speed of about 7 miles per hour on a gravel road. That is the worst condition for the stabilization system. At speeds of up to 25 miles an hour, the frequencies that come in from track slap and from the drive sprockets are between 55 and 58 Hz.

DR. LEIBOWITZ: That is where the eyes start fading. I think that the eye starts to resonate between 50 and 80 Hz. That is where you have visual problems.

DR. HYMAN: But I think there are some Air Force data that show if you are locked in tight, then you jitter at the same rate the display does.

DR. KENNEDY: We are still talking about driving down the roads. I think cross country we find the distances between the trees are not accommodating enough, and so there are abrupt decelerations.

DR. WALBERT: There were some studies done to try to increase the length of the gun turret in order to increase muzzle velocity. One of the biggest problems that was presented for drivers was constantly getting mud in the end of the muzzle. When they go down ditches, they drive the longer muzzle into the ground.

DR. LEIBOWITZ: Well, a good doctrine would be to have the gun aiming back all the time.

DR. HYMAN: No, the doctrine is a herringbone pattern of movement in which more than one tank have their guns lying in opposite directions. But what feedback do you give to the driver so that there is no error in the position of the turret? The display must tell them that the weapon is not aimed in the preferred direction.

Some Observations

JAMES WALBERT

It strikes me that we in the Army should not be talking about wraparound visual displays. It was an interesting idea, and it should be recorded as an interesting idea, but what I gather from the discussion is that it is not a good idea. Do not wrap them around. Do not get carried away with detail or with faithful reproduction of the environment. The display, after all, could probably be made cheaper.

The other thing that stands out from this conference is that things are counterintuitive. One of the things that I have gained is a broadened understanding of motion sickness, which is a key point. When we questioned Sergeant Womer about motion sickness at the last meeting, I am sure he had the same narrow view of what was meant by motion sickness as I did. All of us in the Army are familiar with the Sopite syndrome. We have all gotten up in the morning and said, "I do not really want to go to work today." It would be very difficult to measure the extent to which that broader concept of motion sickness occurs in tank crews.

On the other hand, it is appealing to think that if we somehow designed a system that would overcome motion sickness, we might be able to measure improved crew performance. While a study might be difficult to justify a priori, the potential benefit is a big driving force. We need to consider these factors in the design of the system.

DR. KENNEDY: I think you ought to consider the use of sleep logs. They are used by the Navy and others who perform sleep research to measure the amount of time that people sleep. They are used in the evaluation of various drugs that promote sleep, and there are lots of good logs around.

DR. WALBERT: We are going to have to force the designers to think about these things.

I also heard that training is an important aspect of design, especially today when we were talking about adaptive processes. We like to think in the Army that our machines of war are becoming more and more complex—due in part to our love of technology. But whatever the reasons, they are more complicated machines and, therefore, we think we need a higher level of education among the trainees, that use of these machines requires longer training periods.

What I heard at this conference is that "more complex" does not necessarily mean that it requires "longer training," because it is possible to make a very complex machine for very simplified human interaction, and that is an important point in the training.

In the case of the infantry rifle, there are many studies that show that no matter how much training you have, when the chips are down, instinct takes over and the training goes out the window. In the case of the infantry rifle, study after study has been done by the U.S. Army Human Engineering Laboratory at Aberdeen Proving Ground and others that show, from a benchrest, the rifles are extremely accurate. But as soon as you give them to an individual, the first round hit probability goes way down. There are also questions as to whether the infantry rifle is supposed to be a "real weapon," or whether it is just something to give the man something to hold on to and boost his confidence in combat. There are arguments both ways.

So here is a case in which we can see that all the training in the world goes out the window and instinct takes over. Instinct can be induced by training, however, as any experienced shooter will admit. So, what I would read into the discussion here is that we need to make more aspects of armored vehicles very natural and very instinctive in terms of their operation.

One of the most difficult problems we have when we try to gather information on what is appropriate is the war story problem. Everyone has their own view about what a tank did or did not do. Everyone is convinced that everyone else's war stories are just that, war stories, and that their own experience is real. It may be possible, though, to get some real insight and information by recording the crews as they go through their routine using the technique described by Robert Kennedy (elsewhere in this report). You watch their shortcuts and you watch what they avoid. What we do not have much opportunity to study is the actual use of the fire control systems, since so much of that is confined to the individual's mind and his way of thinking. However, protocol analysis may offer a new opportunity to study this.

The other thing that has been brought out, then, is to look at the tasks, interview the people, and find out about some things that we have not really looked at very hard in terms of tank crews.

The idea of "creature comforts" is extremely important. No one else can position our favorite chair for us to sit in to read; no one else can really arrange the books on our shelf to our liking. We need to have that same sort of feel inside this armored vehicle. That is not to say that the soldier will ever feel at home there, but he certainly needs to feel some level of comfort and security in there. There may be something, in fact, to the Soviet design philosophy; their tanks are very cozy; there is very little room for movement of any sort in that position. There is a connection between that philosophy and the reports here that people who had some control over their motion did not get sick. People need to feel they are in control.

The robotic vehicle is not going to be able to have people in it. We cannot have a robotically driven crew carrier that will take an infantry squad out to a certain point. I do not think anyone would sit still for that. But the idea of computer aiding—with the commander deciding whether or not computer aiding should be used—is something everyone within the military recognizes is going to have to happen.

The other point that must be made is important. As recently as mid-November 1987, we were briefed on a new Standard Damage Assessment List. The list is used in vulnerability analysis and essentially comes from a meeting of mechanics and track vehicle drivers, gunners, and those experienced in the field. You ask a question like the following: "A round comes and hits your turret drive and you can no longer slew the turret. What is the loss of effectiveness of the vehicle?" They sit around the table and try to agree on numbers. It is 20 percent less effective; it is 90 percent less effective; it is 50 percent less effective.

Then we do a live-fire testing of the vehicle. We go in and we assess the damage and we say, this hydraulic line was cut; that fuel line was cut; this air filter was blown out. We put all of that together, looking at what the experienced people have told us. Then we determine, for example, that the vehicle is only 55 percent combat effective at that point.

Part of that study addresses the question: What is the average duration of a mission in the armored vehicle? How long does it take from the time you begin to engage the first target until the time when you begin to turn around and go back home? The average engagement time, up to the point of this new list, was assessed to be 10 minutes. That has changed now. The average engagement time or mission time for a tank is now assessed to be 45 minutes, with the longest mission time being 5 hours. That is a significant change in many respects. It certainly is for vulnerability analysts because if a hydraulic line is pierced and you are dripping hydraulic fluid, you can probably fight for 10 minutes. You cannot fight for 45 minutes, and you certainly could not fight for 2 hours. So when we look at the longer times, it changes the picture of the vulnerability of the systems. It also says something about the duration of the time that a tank may be buttoned up.

DR. KENNEDY: I do not think that it is an adequate representation of the point of view of the crew when the mission time is defined as the time the tank first engages the enemy until the time it withdraws. It should be from the time they get into the tank until the time they get back out of it. Until they engage in combat, there is a long period of underload and then a sudden stressful period, and these are going to interact in some way that we do not yet fully understand. If you are going to evaluate the effectiveness of the tank, it ought to be with the crew too.

DR. WALBERT: That is correct. The point is that we are looking at very long exposure times for this.

In terms of this report, I see it providing a contribution on two levels. The first is that we need to continually make the engineers and the designers aware that there is a vast body of science that needs to come into play when we design anything. Not only is there a vast body of science that has not routinely been consulted in building military vehicles, but also that body of science is accessible. Evidence of the latter point is the group that is assembled here and that is willing to help.

The second is the idea of the "tiger teams." We are always looking at ways to change the structure of an organization. When a team is put together for design, however, I have yet to sit in on any of the test working integration groups that have any representatives from human factors. This is usually because it is too late in the design cycle. Early on in the design cycle, the Army has very little to do with the design cycle, by their choice. They have assigned that role to contractors, and contractors are not necessarily ready to sell some of the human factors designs that we have heard. It is important that we force some of the requests for proposal to begin containing these human factors design considerations.

Again, I want to express my thanks to all of you, to the Committee on Vision, and to the working group for this input. I known that the Ballistics Research Laboratory intends to continue this activity. I would envision the role of this group expanding somewhat and then changing as we get closer to something of a prototype, a simulator, or a mock-up.

Appendix
Protocol Analysis of Military Tasks

ROBERT KENNEDY

It is necessary to have a good idea how vision is used in military ta[illegible]efore performances of such tasks can be proposed for selection or [illegible]ification. This cannot be discovered simply by listing visual cues th[illegible] available in the situation, any more than listing mental activities wou[illegible]ermit similar tests to be used for selection on that basis. We need a way of distinguishing cues that are available from cues that are useful in performing the task. It is the sensitivity to the cues useful in performing tasks that is the important issue in determining the adequacy of selection tests. Because of this we have looked to formal methods of task description and task analysis. Several approaches are available in the research literature for analysis of tasks into behavioral components. Chief among these is the task taxonomy of Fleischman (1967, 1975), the position analysis of McCormick and Jeanneret (1984), the behavioral and information taxonomies of Christianson and Mills (1967), and the critical incident technique of Flanagan (1954). To this list we add a technique by Ericcson and Simon (1984) that is recently being used in laboratories and that is based partially on earlier work of protocol analysis of Newell and Simon (1972). As yet, it has not been tested as an applied tool. A protocol is a taped record and transcription of a subject's verbalizations during the course of landing a military aircraft. It is particularly useful in analyzing phenomena that exhibit strong historical dependence.

In Simon's work (Newell and Simon, 1972; Ericsson and Simon, 1980, 1984), the protocol of the single subject is analyzed and represented first as a problem behavior graph and then as a specific computer program or production system. A problem behavior graph represents what the subject knows and what perceptual, cognitive, and response operations are being applied as a function of time. The experimenter infers what the subject knows from his verbalizations according to a systematic and formal set of procedures, together with the experimenter's knowledge of language and his ability to extract meaning. It is emphasized (Ericsson and Simon, 1980, 1984) that this is not introspection. Only the most obvious components of meaning are used. The protocol, which is a record of utterances at time *t*, indicates states of knowledge and cognitive (information-processing) operations at particular times; it is not a retrospective account. The subject does not theorize about his own protocol as he dictates it. He simply verbalizes what he is doing as he does it. The program or production system is a sequence or list of primitive operations; it is a theory of the subject's behavior. A protocol can be expected to produce the highly specific theory that can be viewed as a single datum point (one per subject) for testing a more generalized theory.

Protocol analysis can be used successfully to characterize the visual requirements for performance of military tasks. By asking experienced operators, such as tank commanders or helicopter pilots, to describe what information they attend to and what they do on a moment-to-moment basis as they do their jobs, a protocol can be generated that permits a description of the necessary visual sensitivities to be developed. Protocol analysis of job scenarios reveals a series of visual tasks against a time line. (Of course, effective use of such a procedure must recognize its limitations. Protocol analysis may not reveal visual cues that are important for performance but which operators are not attending to consciously in the sense of being able to report them. For example, the visual cues for vection may not be reported because vection is a primary reflexive response for postural and gaze stability rather than available for verbal report. Thus, while an operator may report that he is moving, he may not be able to tell us the exact cues he is using. These must be inferred by the protocol analyst. Taking this limitation into account during analysis, protocol analysis may be an effective tool for empirical analysis of the visual requirements of military jobs.)

In addition to reviewing a test of a wider variety of visual functions, we can analyze the performance of a variety of Army jobs believed to depend on vision. We will then be able to map ability measurements to job needs so that we can then describe the usefulness of various tests in selecting individuals for various jobs.

To illustrate this approach we present the outcomes of analysis of protocols from a seaboard helicopter landing and from an observation exercise for tank commanders. These protocols were collected for different purposes than the present one. I will attempt to show how and when the visual functions measured in the five tests described above, as well as one other (static contrast sensitivity), are relevant to these jobs.

HELICOPTER SHIPBOARD LANDING

Concern for the difficulties associated with the helicopter hover-to-landing task aboard seagoing frigates (Del Babb, 1983) has recently prompted interest in the study of these scenarios. Elsewhere and under Navy sponsorship, we selected the LAMPS MK III helicopter as an example of the helicopter shipboard landing problem for analysis because of its currency and importance (Berbaum and Kennedy, 1985). Our objective was to determine which cues are likely to contribute to vehicle guidance at various distances as the ship is approached. We believe the findings are illustrative of work that could be conducted to evaluate military jobs for visual requirements and have excerpted relevant portions below.

We characterize the visual cues that are useful for skilled persons performing a simulator night (dusk) approach in terms of the ranges at which the visual cues become useful in vehicle guidance. The pilot, prompted by another pilot who is more familiar with our objective, dictated verbal protocols of his visual and control activities during several landings. These protocols were analyzed into 10 stages of landing, and the visual information processing within each stage was described. The stages are delimited in terms of range or altitude from the ship.

To discover what visual cues are required for landing outdoors, and thereby to assess those dimensions that are important to provide in simulators, we collected and analyzed a verbal protocol obtained from an experienced helicopter pilot during landing.

Protocol of the SH-60B Flight Simulator Landings Aboard Ship

A test pilot school graduate who had followed the SH-60B helicopter completely through flight testing and acceptance of the aircraft and the dynamic interface with the ship was the pilot. He had approximately 1,000 small-ship landings with about 380 haul down in the SH-60B and a total flight time of about 1,700 hours.

All landings were at night and were essentially done on instruments by using TACAN for lineup until visual cues from the ship could be picked up. There are no visual cues on the side until you hover over the ship. The pilot stated that in an actual landing aboard ship, he picks up side cues from the wave tops and from the wake of the ship, which helps with lining up. Ten successive stages were apparent in the protocol. Table A-1 lists these stages and the distances from or above the flight deck that define them.

These stages are somewhat arbitrary. Some might argue with the exact endpoints. However, they do provide a structure for the analysis.

TABLE A-1 Stages in Helicopter Shipboard Landing

Stage	Distance	Label	Primary Tasks
1	5-4.5 miles	Sighting	Sighting the ship to confirm TACAN
2	4.5-2.5 miles	Instruments	Navigate to the back of the ship using TACAN
3	2.5-1.5 miles	Line-up	Adjust horizontal location relative to ship
4	1.5-1.2 miles	Red/yellow interface	Watch for amber ball to begin descent
5	1.2-0.25 miles	Decelerate (instrument) (visual)	Monitor deceleration (from instrument) monitor line-up and ball color (visual outside)
6	0.25-fantail	Approach (visual)	Visual deceleration approach monitoring
7	Fantail-15 feet	Approach (visual)	Visual deceleration approach monitoring
8	Hover at 15 feet hover above deck	Creep	Slowly move across fantail to light deck hover
9	Hover at 7 feet	Hover tension	Application of tension through cables - final centering
10	Rast landing	Pull down	Application of 4,000 lbs through cables

Our goal in analyzing the protocol was to identify the visual cues that need to be provided by a simulator visual system in order to properly simulate the landing scenarios. In the following sections we present excerpts from the protocol (Jones et al., 1987) and identify primary visual features and functions for the stage.

Stage 1 (5–4.5 miles): Sighting

> What the pilot is doing here is periodically looking out his right window to see if he can pick up the ship yet.

> My peripheral scan will be through the visual system trying to establish in part where the ship is. All pilots have a tendency to rely on eyesight above and beyond everything else that's given. . . .
>
> You're able to differentiate a red light in the upper left and corner; you see a green flashing that indicates a deck status and you see what looks like just a white dot . . . but that white dot is actually going to break itself down into your line-up line itself as we get a little bit closer in.

The visual cues are the ship, a tiny dot, and the wake, a tiny line. Visual acuity and high spatial frequency sensitivity (static) are obviously important. Because the ship and the observer are moving, dynamic visual acuity and contrast sensitivity may also be important. Because the target is distant (e.g., 4.5 to 5 miles), accommodative motility and dark focus are important. Since this is a dusk environment, dark adaptation is relevant.

Stage 3 (2.5–1.5 miles): Line-Up

> Now we're presently at a little over or just under two and a half miles and you're able to start discerning where the line-up line actually is . . . (the line-up line is forming a little bit of an "L"). You can notice there's a slight appendage above the deck strobe, they are indicating that I was slightly off to the left so as a visual backup what I will do is tray and make that vertical line on the front of the hangar line up with the strobe lights that are on the deck and then the 2 red lights can drop down below the deck edge itself.
>
> OK, when that bar centers up you're just astern of the ship. See the yellow ball and the center VHI bar? When that centers up you're right on line. See you're right off the line up. You can tell by the yellow ball, as well as your visual info, you're about 2 1/2 nautical miles away from the ship. You should be able to start picking up a little bit of cueing off the ship. You can see the red cross lines just below the strobes or the deck status: line-up line. You want to make sure that that red light is directly beneath the vertical light on the back of the hangar.

The task is to line up behind the ship for an approach using deck line-up lines, strobe lights, and vertical drop lights. The same dimensions of visual functions are important for the same reasons as in stage 1. In addition, a test of vernier acuity might be predictive of performance in stage 3.

Stage 5 (1.2–0.25 miles): Deceleration

> Notice our alignment is a little off, our heading is a little bit off, because we have a wind not directly on the bow of the ship and so we have to be able to crab, actually we crab the ship itself.

Stage 3 visual tasking continues. The size, shape, and orientation of the ship become important in judging distance and speed. Using relative motion and vection cues, the pilot essentially flies formation with the ship.

Stage 6 (0.25 miles–Fantail): Approach

> Now I'm still maintaining primarily visual outside, looking in at my airspeed in order to see my rate of descent.
>
> Look for closure rate on the visual system itself. Presently we notice the closure rate is usually a little bit fast, so we are adding a little bit of flare.
>
> Closure rate is totally visual at this time, so we are going to go outside almost entirely, going to have to flare because our closure rate is a little bit too fast.

As in stage 5, familiar size and shape provide scale information, which in turn provides distance. Visually induced self-motion perception is driven by the ship features (at increasing size).

Stage 8 (hover at 15 feet): Preliminary Hover

> All I do is maintain position. Notice that the horizon reference bar is now no longer stable as it was before. You can see it moving. The pilot will actually line up the right reference bar with the top of the hangar. If you notice, the right reference bar is low on the left end, not perpendicular; it looks about 8 degrees. Now we're beginning to roll to the right. That's how we can usually tell what the ship itself is doing. That's how I'm keeping my position to it. As the ship rolls a little bit; I anticipate what it's doing—put slight flight control inputs to maintain my position over the deck.
>
> When you put yourself in that position that is so you also can pick up pitch on a ship that way, as the stripes elongate, you know that either the aircraft is climbing or the ship is pitching nose up and they decrease in length, you know the ship is pitching down. You're able to keep track of pitch as well as your position, left or right, up or down.
>
> You maintain your left and right with the line-up lines there, and our altitude is your horizon reference system itself.

Flight control devices on deck are monitored to maintain level flight (to avoid flying formation with the ship via vection and postural stability mechanisms). The pitch of the ship is monitored by the relative motion of the deck lines. Motion parallax and interposition are important.

The ambient visual system is ontogenetically earlier than other parts of the visual system and is less likely to be modifiable. It takes visual

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Flight control devices on deck are monitored to maintain level flight (to avoid flying formation with the ship via vection and postural stability mechanisms). The pitch of the ship is monitored by the relative motion of the deck lines. Motion parallax and interposition are important.

The ambient visual system is ontogenetically earlier than other parts of the visual system and is less likely to be modifiable. It takes visual information from a large area of the visual field and computes self-motion directly. This becomes particularly important in a simulator, where there are not appropriate vestibular cues, but only linear vection cues, available. The pilot's rapidly and directly perceived velocity, position in space, and orientation in space are all determined by the visual analysis of large features in this last 50 to 75 feet.

Summary

For helicopter shipboard landing, dark adaptation, accommodative motility and dark focus, and dynamic visual acuity and contrast sensitivity are most important in the early phases, such as during sighting and line-up. Vection and dynamic contrast sensitivity are most important for the late phases of landing, such as deceleration, approach, and hover.

TANK COMMANDER

This is the first observation exercise stressing the use of fields of fire observation, cover and concealment obstacles, lines of communication, and careful observation of the terrain on both sides. A protocol was dictated by a retired Army colonel who had well over 25 years of active duty in the Armor division:

> It is approximately 4:30 in the afternoon, weather conditions are clear, the area is afternoon/evening dusk, first position is a gently rolling piece of terrain. The terrain would require careful travelers with covering fire, dangerous direction, right and left. Most of the heavily wooded area would probably not be attempted unless they were cleared, either by artillery or infantry force. Some of the long-range vistas would have to be traversed *quite quickly with considerable covering* from overwatching tanks.
>
> At a greater distance through the trees is a large rectangular object which could readily be an armored vehicle or a small truck. There are standing people in the trees moving around. Moving the eyes almost to the immediate front at a greater distance there is a large draw.
>
> As the eye goes further to the right the road continues and at a greater distance a large building, again a concealed position for armor, and as the eye carries down further right at greater distance the road continues and it's heavy trees and a wide-open field of fire.
>
> Moving down the road further into open terrain with high bank brush concealment on each side, trees on the right and left down the trail, immediate trees straight ahead, causing sharp turns to the left down another trail with trees immediately to the right-front of the vehicle.

> Proceeding about 5-10 miles per hour the buildings are small, which could conceal a firing position. Coming immediately up to the left-hand side, again as we proceed further, is a group of woods. Going straight on down now we have an open extended area with more tree lines to the right and left offering plenty of concealment. The eyes are wandering back and forth looking for infantry concealed areas.
>
> My eye automatically goes to the right to seek out the terrain as I move to try to observe to see if I can see flashes or any sign of vehicles.
>
> Another trail swings off to the left with a building immediately to the front and as I look an extremely vulnerable position searching for buildings and looking at windows, seeking signs of activity both right and left, traversing quickly.
>
> As I look on down further, scanning down way ahead, I see the road extend for about 2 miles and on the left again the tree line has opened up again to open flat meadowland with small trees, shrubs, flat open country, again a full field of fire. And now to the right the terrain has opened to a large vista with about a 2-mile visibility with rolling terrain and then a definite position on this trail on the right and left with good wide vistas for sweeping-eye contact looking for flashes—extremely vulnerable. Moving quickly across there to the left to explain in greater detail large trees, large groups of woods to the left, a small building, a good opportunity to conceal armor.

From these excerpts it is clear that the tank commander is engaging in a lot of search for targets (enemy vehicles). Considering the distances involved and the rapid changes in focus, measures of accommodation and dark focus may be very predictive of performance in this task. Acuity and static high-frequency contrast sensitivity are certainly important in detecting and identifying the targets. Given that the observer is often moving, sometimes quite rapidly, dynamic visual acuity and dynamic contrast sensitivity may be important. Gaze stability may be important.

Military jobs differ in the kinds of visual functions they require. The two job scenarios analyzed here, helicopter shipboard landing and tank commander, are more similar than different in terms of visual requirements. Other jobs such as radar image interpretation or medical pathology or control panel operations will have very different requirements. In many cases the selection of an individual on the basis of sensitivities may not be critical. However, for some military jobs, successful performance will be determined by such sensitivity. Determining the visual sensitivities critical to performing certain critical jobs is necessary for selecting tests of visual performance on the basis of relevance.

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Glossary

Accommodation. The ability of the eye to adjust to objects located at varying distances by changing the focal length of the lens.

Accommodative lag. The failure to accommodate the full amount demanded for the sharpest image of the stimulus object.

Asthenopia. A term generally used to designate any subjective symptoms or distress arising from use of the eyes.

Astigmatism. Defocus in an optical system attributable to lens or mirror surfaces that act as though they were characterized by two different radii of curvature.

Ataxia. An inability to coordinate muscular movements.

Cognitive coherence. A design concept or principle of aiding one's grasp of a total situation by presenting two or more related information subdisplays in a manner so they logically and partially redundantly reinforce each other.

Doll reflex. Rotation of the eyes in a direction opposite to a head movement, through an angle considerably smaller than the head movement, with a subsequent return toward the original position.

Gaze stability. A term for when the eyes remain fixated at the same place in space by compensating for head movements.

Field of view. The solid angle included by an optical system. In electro-optical application the field of view of the sensor combined with the display is usually greater in the horizontal dimension.

Heterophoria. The tendency of the lines of sight to deviate from the relative positions necessary to maintain stable binocular single vision for a given distance of fixation.

Isomorphism. In Gestalt psychology, the presumed or implied similarity of organization or pattern of conscious content, such as visual perception, and the simultaneously present cerebral cortex activity.

Isoperformance. A conceptual approach to human factors engineering. Its focus is to maintain the same level of system performance by different combinations of personnel, training, and equipment variations.

Luminance. The photometric term for the intensive property of an emitting or reflecting surface.

Monocular viewing. Pertaining to or affecting one eye.

Nystagmus. Regularly repetitive, usually rapid, and characteristically involuntary movements or rotations of the eye, either oscillatory or with slow and fast phases in alternate directions.

Oculogyral illusion. An illusion that occurs when someone is accelerated in an angular fashion while the person is looking at a target that is fixed relative to the person's body. The person will see apparent motion of that target light in relation to the body. Detection of illusory displacement can occur before one can detect any apparent eye movement (nystagmus) response.

Plasticity. Changes in parameters of adaptive oculomotor control systems that are retained, even after the adapting conditions are removed, until new demands for change are made.

Sopite syndrome. A kind of chronic fatigue and lethargy that one gets from long-term, low-grade exposure to motion.

Spatial frequency. The number of cycles per unit length of a pattern whose quantized energy flux density varies periodically in one of the dimensions of space.

Spatial resolution. The ability to perceive two target elements as two separate elements.

Spherical aberration. A monochromatic aberration occurring in simple refraction at a spherical surface, characterized by peripheral and paraxial rays focusing at different points along the axis. In virtual image displays, spherical aberration causes changes in accommodative and convergence demand from the intended image location at optical infinity.

Telepresence. Systems that are designed to transform as well as transport and to perform wide-ranging, complex, and uncertain tasks. Systems that sense highly detailed patterns of visual, auditory, and tactile information in the remote environment and display the nonharmful, task-relevant components of this information to an operator in a way that very closely replicates the pattern of stimulation available to an on-site observer.

Torsion. Rotation, or more specifically cyclorotation, of the eye around an anteroposterior axis such as the fixation axis.

Vergence. A disjunctive rotational movement of the eyes such that the points of reference on the globes move in opposite directions, as in convergence, cyclovergence, or sursumvergence.

Vestibulo-ocular reflex (VOR). Very brief head movements which cause the appropriate conjunctive coordinating movement of both eyes in a direction opposite to head movement. These movements also can be initiated by the application of thermal stimuli to the eardrum and by radially accelerated gravitational force vectors.

Visual adaptation. The ability of the retina to adapt its sensitivity to varying illumination levels. The term also refers to the capability of certain oculomotor systems to change gain and phase parameters.

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