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TELEPRESENCE, TIME DELAY, AND ADAPTATION

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INTRODUCTION

Displays, which are the subject of this conference, are now being used extensively throughout our society. More and more of our time is spent watching television, movies, computer screens, etc. Furthermore, in an increasing number of cases, the observer interacts with the display and plays the role of operator as well as observer. To a large extent, our normal behavior in our normal environment can also be thought of in these same terms. Taking liberties with Shakespeare, we might say that "all the world's a display and all the individuals in it are operators in and on the display."

Within this general context of interactive display systems, we begin our discussion with a conceptual overview of a particular class of such systems, namely, teleoperator systems. We then consider the notion of telepresence and the factors that limit telepresence, including decorrelation between the (1) motor output of the teleoperator as sensed directly via the kinesthetic/tactual system, and (2) the motor output of the teleoperator as sensed indirectly via feedback from the slave robot, i.e., via a visual display of the motor actions of the slave robot. Finally, we focus on the deleterious effect of time delay (a particular source of decorrelation) on sensory-motor adaptation (an important phenomenon related to telepresence).

I. TELEOPERATOR SYSTEMS

A schematic outline of a highly simplified teleoperator system is presented in figure 1. As pictured, the major components of a teleoperator system are a human operator, a teleoperator station (or "suit"), a slave robot, and an environment which is sensed and acted upon by the slave robot. As indicated by the arrows flowing from left to right, sensors on the slave robot are stimulated by interaction with the environment, the outputs of these sensors are displayed in the teleoperator station to the sensors of the human operator, and the received information is then transmitted to higher centers (brain) within the human operator for central processing. As indicated by the arrows flowing from right to left, the central processing results in motor responses by the human operator which are detected in the teleoperator station and used to control motor actions by the slave robot. The upward flowing arrows depict the role played by the motor system (at both the slave robot and human operator levels) in controlling the sensors and therefore the flow of information from environment to brain.

The normal situation in which the human interacts directly with the environment can be pictured as a special case of the teleoperator situation by ignoring the teleoperator station and identifying the slave robot's sensors and effectors with those of the human operator. Similarly, imaginary or virtual environments can be pictured in terms of the teleoperator situation by retaining the human operator and teleoperator station, but replacing the real environment and slave robot by a computer simulation. Finally, robotic systems can be realized by replacing the human operator and teleoperator station by an automatic central processor, and interpolations between teleoperator systems and robotic systems can be realized by assigning lower-level control functions to automatic processing and higher-level control functions (supervisory control) to the human operator.

Note also that the sensor and effector channels need not be restricted in the manner illustrated in Fig. 1. Not only are there many cases in which the visual channel pictured would be paralleled by an auditory channel, but for certain purposes the slave robot might also include sensors for which the human has no counterpart (e.g., to sense infrared energy or magnetic fields). Furthermore, on the response side, the teleoperator station might detect and exploit responses other than simple motor actions. For example, it might be useful for certain purposes to measure changes in skin conductivity, pupil size, or blood pressure.

In general, the purpose of a teleoperator system is to augment the sensory-motor system of the human operator. The structure of the teleoperator system will depend on the specific augmentation envisioned, as well as on the technological limitations. A continuum that relates directly to the issue of telepresence considered below concerns the extent to which the structure of the slave robot is the same as that of the teleoperator. At one extreme are systems meant simply to transport the operator to a different place. In the ideal version of such a system, the slave robot would be isomorphic to the operator and the various sensor and effector channels would be designed to realize this isomorphism. In a closely related set of systems, the basic anthropomorphism is preserved, but the slave robot is scaled to achieve, for example, a reduction of size or magnification of strength. At the opposite extreme are systems involving radical structural transformations and highly non-anthropomorphic slave robots. In these systems, there is no simple correspondence between slave robot and human operator, and the design and organization of the sensor and effector channels generally becomes very complex and difficult to optimize, even at the abstract conceptual level. General reviews of teleoperation and teleoperator systems can be found in Johnsen and Corliss, 1974, and Vertut and Coiffet, 1986.

II. TELEPRESENCE

Although the term "telepresence" is often used in discussions of teleoperation, it never has been adequately defined. According to Akin et al. (1983), telepresence occurs when the following conditions are satisfied:

> "At the worksite, the manipulators have the dexterity to allow the operator to perform normal human functions. At the control station, the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite."

A major limitation of this definition is that it is not sufficiently operational or quantitative. It does not specify how to measure the degree of telepresence. Also, as indicated by the phrase "perform normal human functions" in the first sentence, it fails to address the issue of telepresence for systems that are designed to transform as well as transport and to perform abnormal human functions.

Independent of the precise definition of telepresence, why should one care about telepresence? What is it good for? Certainly, there is no theorem which states that an increase in telepresence necessarily leads to improved performance. In our opinion, a high degree of telepresence is desirable in a teleoperator system primarily in situations when the tasks are wide-ranging, complex, and uncertain, i.e., when the system must function as a general-purpose system. In such situations, a high degree of telepresence is desirable because the best general-purpose system known to us (as engineers) is us (as operators). In a passage that is relevant both to this issue and to the definition of telepresence, Pepper and Hightower (1984) state the following:

> "We feel that anthropomorphically-designed teleoperators offer the best means of transmitting man's remarkably adaptive problem solving and manipulative skills into the ocean's depths and other inhospitable environments. The anthropomorphic approach calls for development of teleoperator subsystems which sense highly detailed patterns of visual, auditory, and tactile information in the remote environment and display the non-harmful, 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. Such a system would permit the operator to extend his sensory-motor functions and problem solving skills to remote or hazardous sites as if he were actually there."

In addition to the value of telepresence in a general-purpose teleoperator system, it is likely to be useful in a variety of other applications. More specifically, it should enhance performance in applications (referred to briefly in Sec. I) where the operator interacts with synthetic worlds created by computer simulation. The most obvious cases in this category are those associated with training people to perform certain motor functions (e.g., flying an airplane) or with entertaining people (i.e., providing imaginary worlds for fun). Less obvious, but equally important, are cases in which the system is used as a research tool to study human sensorimotor performance and cases in which it is used as an interactive display for data presentation (e.g., Fisher, 1987; Bolt, 1984).

An important obstacle at present to scientific use of the telepresence concept is the lack of a well-defined means for measuring telepresence. It should not only be possible to develop subjective scales of telepresence (using standardized scale-construction techniques), but also to develop tests, both psychological and physiological, to measure telepresence objectively. For example, some test based on the "startle response" might prove useful. Certainly, such a test could distinguish reliably between different degrees of realism in the area of cinematic projection. Also, of course, given both some subjective scales and some objective tests, it would be important to study the relations among the two types of measures.

Beyond questions related to the definition and measurement of telepresence, the core issue is how one achieves telepresence. In other words, what are the factors that contribute to a sense of telepresence? In fact, what are the essential elements of just plain "presence?" Or alternately, looking at the other side of the coin, how can the ordinary sense of presence be destroyed (short of damaging the brain)?

Given the vague and qualitative character of definitions and estimates of telepresence, it is not surprising that there is no scientific body of data and/or theory delineating the factors that underlie telepresence. Our remarks on this topic thus make substantial use of intuition and speculation, as well as extrapolation from results in other areas.

Sensory factors that contribute to telepresence include high resolution and large field of view. Obviously, reduction of input information either by degraded resolution or restricted field of view will interfere with the extent to which the display system is transparent to the operator. Perhaps these two variables are tradeable in the sense that the effective parameter in determining the degree of telepresence is the number of resolvable elements in the field, or, equivalently, for fields with uniform resolution over the field, Area of Field/Area of Resolvable Element. Also important, of course, is the consistency of information across modalities: the information received through all channels should describe the same objective world (i.e., should be consistent with what has been learned through these channels about the normal world during the normal development process). In addition, the devices used for displaying the information to the operator's senses in the teleoperator station should, to the extent possible, be free from the production of artifactual stimuli that signal the existence of the display. Thus, for example, the visual display should be sufficiently large and close enough to the eyes to prevent the operator from seeing the edges of the display (or anything else in the teleoperator station, including the operator's own hands and body). At the same time, the display should not be head-mounted in such a way that the operator is aware of the mounting via the sense of touch. Clearly, attempting to satisfy both of these constraints simultaneously is a very challenging task.

Motor factors necessary for high telepresence involve similar issues. Perhaps the most crucial requirement is to provide for a wide range of sensorimotor interactions. One important category of such interactions concerns movements of the sensory organs. It must be possible for the operator to sweep the direction of gaze by rotating the head and/or eyeballs and to have the visual input to the retinas change appropriately. This requires using a robot with a rotating head, the position of which is slaved to the position of the operator's head. The desired result can then be achieved in two ways, depending upon whether the system is designed to have the position of the robot's eyeballs (1) fixed relative to the the robot's head (e.g., pointing straight ahead) or (2) slaved to the position of the operator's eyeballs in the operator's head. In the first case, appropriate results can be obtained using binocular images that remain fixed relative to the operator's head position during eyeball scanning. In the second case, the positions of the projected images must be slaved to the position of the operator's eyeballs. If they were instead held fixed, then whenever the operator's eyeballs were rotated, the projected images would rotate. For example, if the operator's eyeballs were rotated to look at an object whose images were on the right side of the projection screens, the slave robot's eyeballs would rotate to the right, the images of the object in question would move to the center of the two screens, and these images would then be sensed to the left of the foveal region. In order to eliminate this problem, the projected images would also have to be rotated to the right. In other words, if the position of the robot eyeballs are slaved, the position of the projected images must also be slaved. To the best of our knowledge, no such system has yet been developed (although monitoring of operator eyeball position is being used to capitalize on reduced resolution requirements in the peripheral field in the pursuit of reduced bandwidth).

Another category of sensorimotor interactions that is essential for high telepresence concerns movements of viewed effectors. It must be possible for the operator to simultaneously move his/her hands (receiving the internal kinesthetic sensations associated with these movements) and see the slave robot hands move accordingly. Also, as with the sensory display, the devices used in the teleoperator station to detect and monitor the operators movements should, to the extent possible, be undetectable to the operator. The more the operator is aware of these devices, the harder it will be to achieve a high degree of telepresence. An amusing picture that is addressed to the issue of viewing one's own effectors, or more generally, one's own body parts, and that is of some historical interest, is shown in figure 2 (Mach, 1914).

The most crucial factor in creating high telepresence is, perhaps, high correlation between (1) the movements of the operator sensed directly via the internal proprioceptive/kinesthetic senses of the operator and (2) the actions of the slave robot sensed via the sensors on the slave robot and the displays in the teleoperator station. Clearly, the destruction of such correlation in the normal human situation (in which the slave robot is identified with the operator's own body) would destroy the sense of presence.

In general, correlation will be reduced by time delays, internally generated noises, or non-invertible distortions that occur between the actions of the operator and the sensed actions of the slave robot. How these variables interact, combine, and trade in limiting telepresence and teleoperator performance is a crucial topic for research. In sec. III, we look more closely at the effects of one of these variables, namely, time delay.

Note also that telepresence will generally tend to increase with an increase in the extent to which the operator can identify his or her own body with the slave robot. Many of the factors mentioned above (in particular, the correlation between movements of the body and movements of the robot) obviously play a major role in such identification. Additional factors, however, may also be important. For example, it seems plausible that identification, and therefore telepresence, would be increased by a similarity in the visual appearance of the operator and the slave robot.

Finally, it is important to consider the extent to which telepresence can increase with operator familiarization. Even if the system is designed merely to transport rather than to transform, it will necessarily involve a variety of transformations that initially limit the sense of telepresence. A fundamental topic for research concerns the extent to which such limitations can be overcome by appropriate exposure to the system and development of appropriate models of the transformed world, task, self, etc. (through adaptation, training, learning, etc.). Figure 3 illustrates schematically how the internal dynamics of the operator are originally established and may be altered over time when interaction with the world is transformed. The representation (in brain) of the operator's interaction with the world is an important factor in the sense of presence. The operator identifies his or her own actions as such in accord with the concomitant sensory changes. Loss of such concomitance may reduce the sense of presence. But an updating of the internal model may promote the recovery of a lost sense of presence within that world. The figure shows how the motor command originating in the central nervous system (CNS) activates the musculature which in turn causes sensory changes which feed back to the CNS. The comparator is designed to receive a feed-forward signal from the internal model, which derives from past experience and anticipates the consequences of activity based upon that previous experience. That signal is then compared with the contemporary consequenc:es of action. Any transform in the feedback loop will alter the expected feedback and be discrepant with the feedforward signal. In that event, the discrepant signal may be used to update the world model and lead to more accurate anticipations of action and an improved sense of presence.

III. TIME DELAYS AND ADAPTATION

Time delays between action of the teleoperator and the consequences of these actions as realized on the displays in the teleoperator station can arise from a variety of sources, including the transmission time for communication between the teleoperator station and the worksite and the processing time required for elaborate signal-processing tasks. Independent of the causes, it is clear that such feedback delays degrade both telepresence and performance. Research on the effects of time delays on manual tracking and remote manipulation and on methods for mitigating these effects are discussed in a variety of sources (e.g., Adams, 1962; Arnold and Braisted, 1963; Black, 1970; Ferrell, 1965, 1966; Johnsen and Corliss, 1971; Kalmus, Fry, and Denes, 1960; Leslie, 1966; Leslie, Bennigson, and Kahn, 1966; Levison, Lancraft, and Junker, 1979; Pennington, 1983; Pew, Duffenbach, and Fensch, 1967; Poulton, 1974; Sheridan, 1984; Sheridan and Ferrell, 1963,1967,1974; Sheridan and Verplank, 1978; Starr, 1980; Wallach, 1961; Wickens, 1986). Of particular interest has been the development of systems that combat the effects of time delay through judicious supplementation of human teleoperation by automatic processing (involving predictive models and use of the human operator for supervisory control).

The particular effect of time delay on which we shall focus in the remainder of this paper is the effect on sensory-motor adaptation. As suggested at the end of the last section, the degree of telepresence that can be achieved with a given system depends ultimately on the extent to which the operator can adapt to the system.

Basic demonstration of adaptation was discussed by Helmholtz in his Physiological Optics (Helmholtz, 1962). In the typical experiment, the subject wears prism spectacles over his or her eyes which optically shift the apparent location of objects seen through them. When the subject reaches for a seen target without correction (open loop), the termination of his or her reach will obviously be in error by an amount approximating the apparent displacement of the target produced by the prism. Correction of a reach can be prevented in one of two ways. If the subject (S) is required to make a rapid ballistic movement of his or her hand to the target, the duration of hand travel is too short to allow correction. However, if both target and hand are visible at the termination of the reach, the error may be noted by S and subsequent reaches corrected. Alternatively, the target may be presented in a location where the hand may reach but not be seen. Following the initial measurements of reaching accuracy, the subject views either his or her hand or a surrogate for it through the prisms for a period of time called the exposure period. During that period he may or may not receive visual information concerning the error of the reaching. Following the exposure period a second measure is obtained of the accuracy of open loop reaching for visible targets. The result is generally a decrease of error from that of the initial localizations in a direction which indicates correction for the presence of the prism displacement. Further open-loop measurements may be made with the prisms removed, in which case the error of reaching for a target increases. This increased error shows that the shift in localization is not dependent upon the presence of the prisms, but is a more generalized change in eye-hand coordination adaptive for the presence of the prisms.

Some sort of adaptive process occurs during the exposure period which compensates for the error introduced by the prism. Information available during the exposure period produces an update of the internal model of the visuospatial coordinates which are anticipated as the goal of reaching for the target. The nature of the necessary and sufficient information required for adaptation, and of the subsystems that actually adapt, has been the subject of much debate and experimentation (Welsh, 1978, 1986). It appears that any of a number of sources of information about the transformed relation between the seen position of the hand and its location as known through other information may serve to produce adapation. One such source of information is the error seen when reaching for targets. When the reaching subject can see the error, he or she is bound to correct for it by a process of which he or she is usually quite conscious. Among other cognitive factors, knowledge of the optical effects of the prism may enhance adaptive responses. Active movement of the arm which produces visual feedback enhances adaptation, perhaps by sharpening the sense of position of bodily parts. More interesting from several points of view is the adaptive process which occurs during exposure when visible error feedback appears to be absent. For example, subjects adapt while looking through the prism at only a luminous spot fixed to the hand in an otherwise dark field. The spot moves with the hand, but when no other targets or even visible landmarks are present, there can be no explicit visible error. There may, however, be a discrepancy with the expectations based upon the concomitance of visual location of the hand with its non-visually sensed position. But this condition raises a further question. If the subject sees only a luminous spot on the hand as it moves, how does the nervous system identify this spot with the sensed positions of the hand? Aside from cognitive factors, we must hypothesize that the movements of the visible spot concomitant with the sensed movements of the hand allow this identification. The problem then becomes one of correlation between signals. Moreover, we recognize that this form of identification may well be a basis for establishing presence itself. This realization led to the following experiment.

The experiment concerns the effect of time delay on adaptation of eye-hand coordination to prism displacement. Changes in the seen position of the hand are delayed during a period of exposure between test and retest. For a given exposure, the delay is fixed, but over a series of exposures, the delay is varied. The question we asked was: What are the effects of delaying feedback by various amounts on the adaptive process that takes place during exposure with continuous monitoring by the subject of his or her hand movements in a frontal plane? In other words, how much is the effective correlation of identifying signals degraded by delay of visual feedback of varying intervals? In an earlier experiment (Held, Efstathiou, and Greene, 1966), we found that delays as small as 300 msec eliminated adaptation to prism displacement. Consequently, the following experiment incorporated delays of smaller magnitude.

As shown in figure 4, the subject (S) stood at the apparatus. He positioned his head in a holder mounted on top of a light-proof box and looked down through an aperture into a mirror. The mirror reflected the image of a luminous spot, formed on a ground glass screen, which appeared on an otherwise dimly illuminated background. The image originated on an oscilloscope face and was focused on the screen. S's right hand grasped a handle consisting of a short vertical rod located at arm's length beneath the box. The rod was attached to a lightweight roller-bearing arrangement which minimized inertia and friction but restricted hand movements to a region in the horizontal plane. When the hand moved the cursor, sliding contacts were driven along two linear potentiometers aligned at right angles to each other. This movement varied DC signals corresponding to the coordinates of the cursor on the horizontal surface. These signals were applied to the vertical and horizontal channels of the oscilloscope, thereby producing a single spot on the screen, the position and motion of which corresponded to that of the cursor. The optical system (lens and mirror) caused the spot to appear superimposed on the handle of the cursor when neither positional displacements nor temporal delays were introduced. The apparatus could be set to displace the spot 1.5 in. laterally to either the right or the left side. Temporal delays ranging from 20 to 1,000 msec could be introduced in either the lateral or the vertical dimension, or both.

In addition to driving the trace by movements of the cursor, the loop could be opened and the trace spot set to display, one a a time, five stationary visible targets. The target coordinates were determined by applying paired X and Y voltages to the oscilloscope under the experimenter's control. Ss were instructed to set the handle of the cursor so that the top of the vertical rod felt superimposed on the visible target. Ss pressed a switch when they felt that the cursor was correctly positioned and the position was recorded.

Ss were 12 right-handed male college undergraduates with adequate vision and were naive as to the purpose of the experiments. Each S performed six runs separated by rest periods. Each run consisted of six steps:

1. Practice. S was instructed to track the luminous spot with his eyes as he moved the cursor back and forth across the horizontal surface and to change the left-right direction of his hand movement with the beat of a metronome. This beat varied in a 60-sec cycle from 50 to 90 beats/min. Practice lasted a minute or two during which the subject traced the limits of movement of the cursor. He was instructed to avoid hitting the limiting stops during subsequent exposure and target localization, thus eliminating one potential source of information regarding the position of his hand on the surface.

2. Pre-Exposure Localization. S was instructed to look at and localize the apparent positions of each of the five visual targets presented four times in a pseudo-random sequence. The moveable spot was extinguished prior to target presentations and the subject was instructed to move the cursor randomly about the surface before and between target presentations.

3. First Exposure. S performed for 2 min as he did during the practice period. Both positional displacement and delayed visual feedback were introduced. One of six delay conditions, 0, 120, 150, 210, 330, and 570 msecs, was presented during each run. The six delays were presented to each S in a different order; half of the Ss were exposed to the spot laterally displaced in one direction (right or left) during this exposure and half with the same order of delayed conditions, but with the direction of displacement in the opposite direction.

4. First Post-Exposure Localization. Identical to the pre-exposure localization.

5. Second Exposure. Identical to the initial exposure, but with lateral displacement in the opposite direction.

6. Second Post-Exposure Localization. Same as pre-exposure localization.

The results were analyzed by taking the differences between the first and second post-exposure localizations as the primary measure of compensatory shift. These differences tend to be larger and more reliable than those between pre-exposure and post-exposure localizations (Hardt, Held, and Steinbach, 1971).

Four experiments were performed. They were identical except for variations in the exposure procedure. In the first experiment, S tracked the hand-driven spot with his eyes as described above. In the second, S's eyes fixated a dim cross during exposure, thereby precluding tracking of the spot with the eyes. In the third, each S was trained to relax his arm while grasping the cursor and the experimenter moved the cursor in the manner discussed above (passive condition).

The fourth experiment was identical to the second except that two shorter time delays were used, namely, 30 and 60 msec.

The S's mean compensatory shifts at various time delays are shown in figure 5. The overall effect of delay in the first experiment (no fixation) is significant. All of the mean shifts are different from zero and all the shifts under delay are significantly less than the shift at zero delay. The results of the second experiment (fixation) did not differ significantly from those of the first, showing that tracking the hand-driven target with the eyes was not a factor in promoting adaptation. While the passive condition of the third experiment reduced the overall level of adaptation, significant adaptation still occurred, and the overall shape of the curve with delay was similar to that of the active conditions. Finally, the effects of very short delays in the fourth experiment did not differ significantly from zero delay, although delays of 120 msec clearly do reduce adaptation. We conclude that delays must exceed 60 msec if they are to be sufficient to reduce adaptation significantly under the conditions of the experiment. For reasons we do not understand, the curves appear to asymptote at 30 to 40% of compensation under zero delay.

It should also be noted that subjective impressions varied strongly with the delay. At the shorter delays (not too far above threshold), the viewed hand seems to be suffering simply a minor lag, as if it were being dragged through a viscous medium. At delays beyond a couple of hundred msec, however, the image seen becomes more and more dissociated from the real hand (i.e., identification, and therefore presence, breaks down).

In general, it is obvious that some degree of identification is necessary in order for adaptation to occur. Moreover, when adaptation occurs, it is obvious that identification increases. Thus, adaptation and identification (and therefore telepresence) must be very closely related. Note, however, that adaptation will fail to occur when either (1) no identification is possible or (2) identification is complete. Thus, tests of adaptation cannot, by themselves, be used to measure identification; other kinds of tests must also be included. Clearly, a precise characterization of the relations between adaptation, identification, and telepresence (or presence) requires further study.

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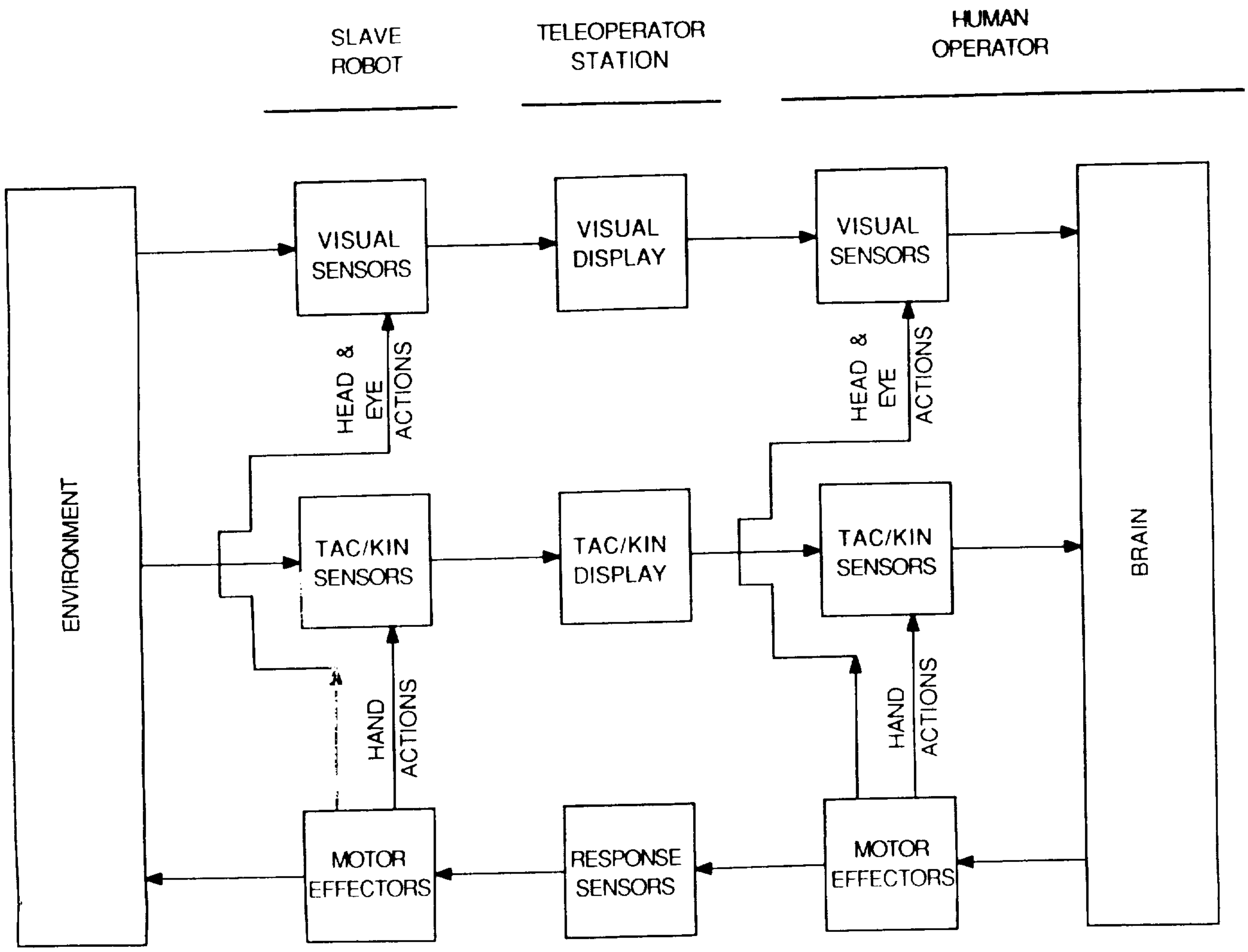

Figure 1.– Schematic outline of teleoperator system.

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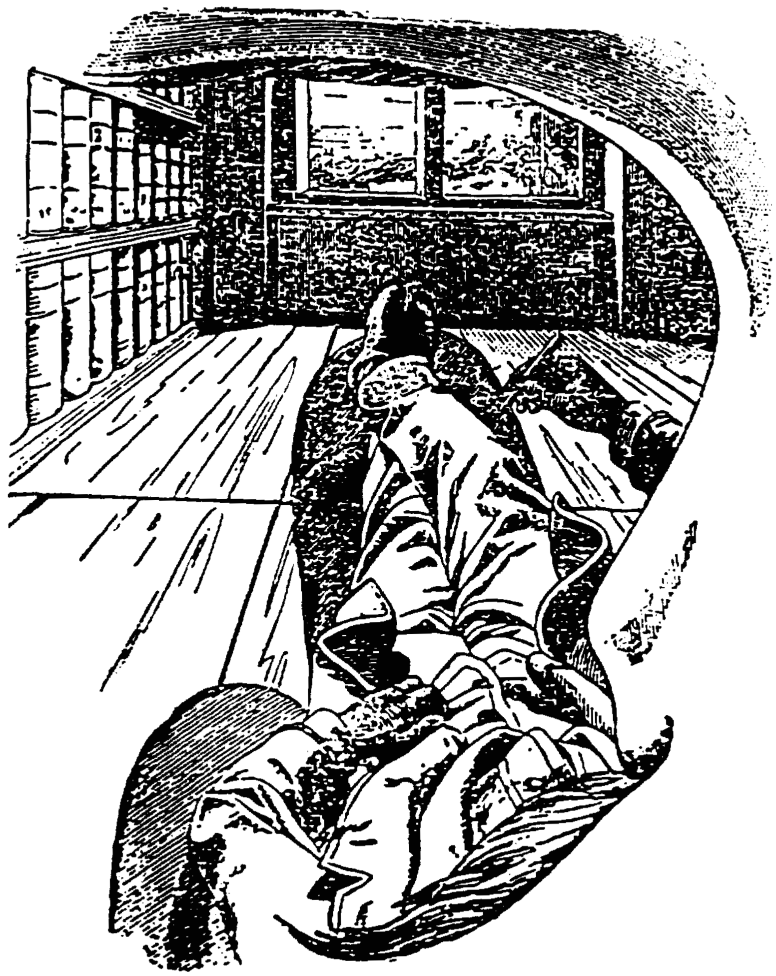

Figure 2.– Mach observing visible parts of his own body and the surroundings.

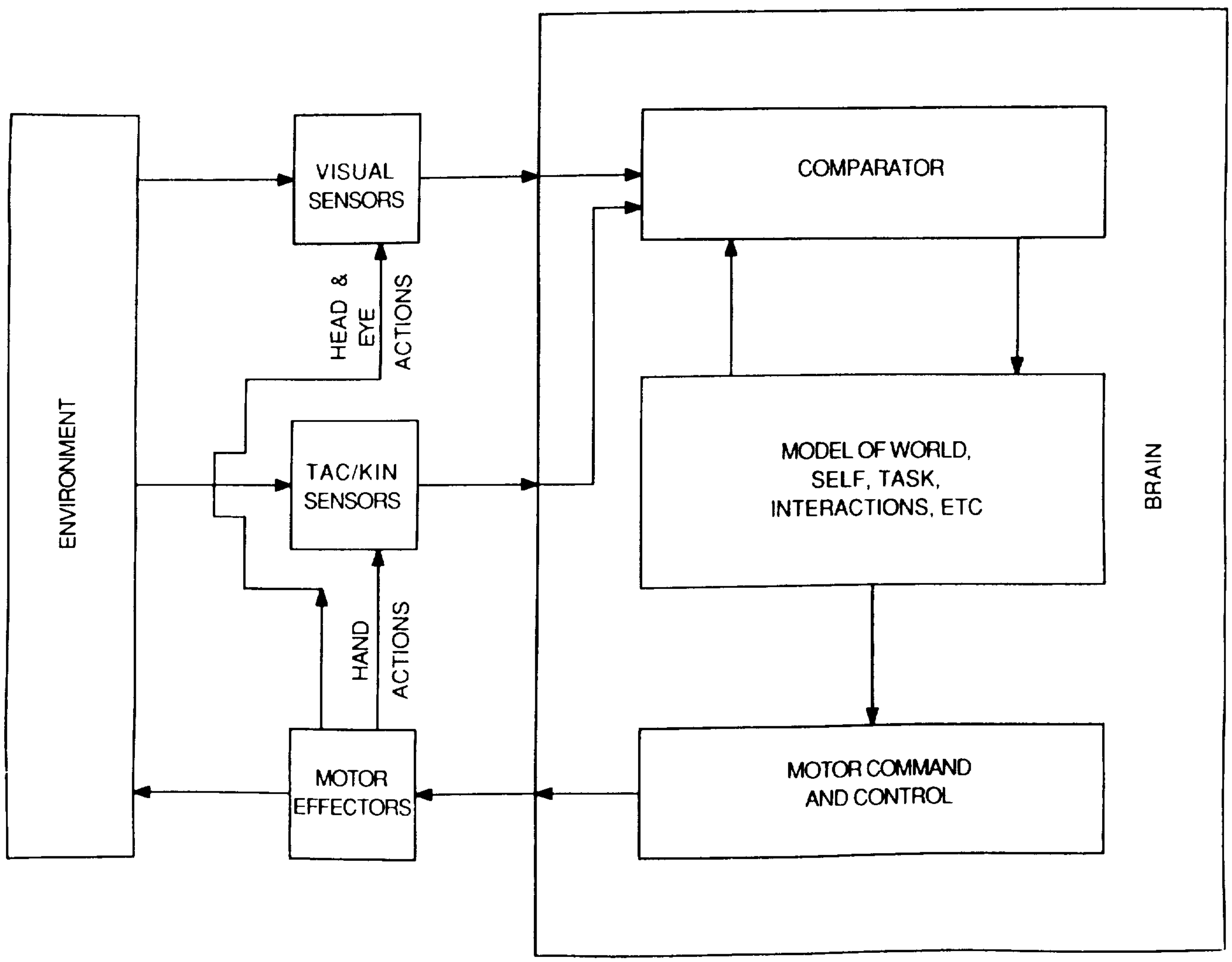

Figure 3.– Information flow and feedback loops involved in actions of the operator in the environment.

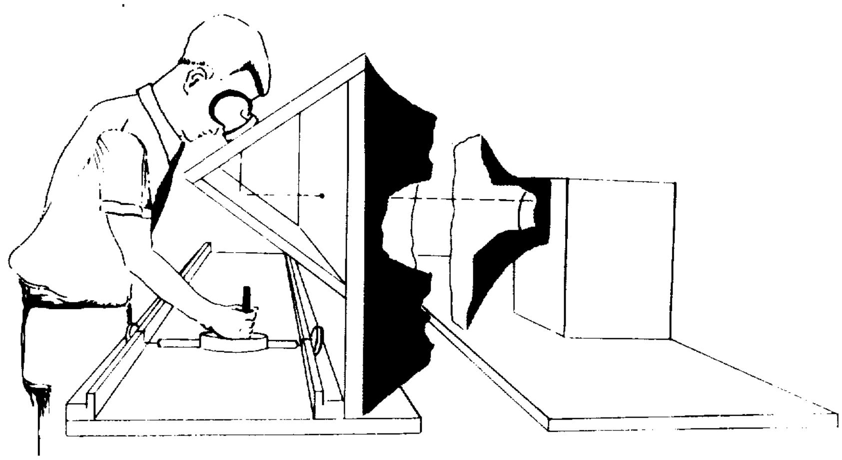

Figure 4.– Experimental setup for studying adaptation to visual displacement and delay.

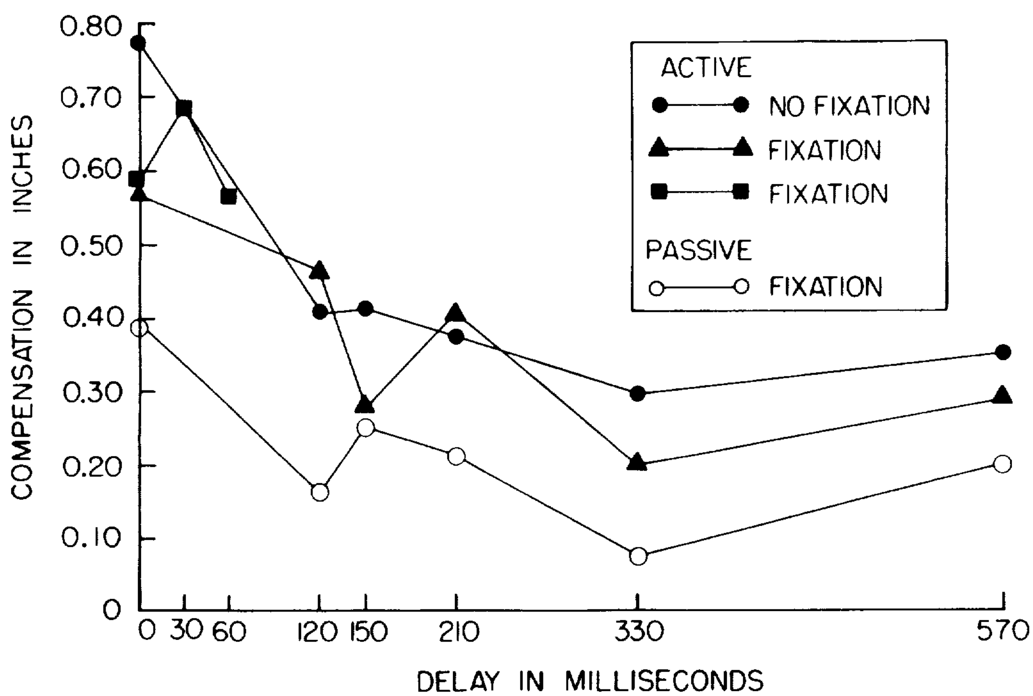

Figure 5.– Results of experiments.