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Plasticity in Human Sensorimotor Control

Studies of disordered motor-sensory feedback raise questions about man's coordination in outer space.

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Can man function effectively, let alone survive, in the exotic environments to which the astronaut will be exposed? The answers promise to be of scientific interest as well as practical consequence. Optimistic forecasts have been made of man's ability to perform efficiently in outer space for indefinitely long periods. These predictions have generally been based upon observations of human adaptability to the many and diverse circumstances found above, below, and on the surface of the earth. Some of the conditions to be encountered in space have been simulated by existing equipment on earth, and their consequences for human performance have been tested. Other conditions cannot be so directly tested, and informed speculation becomes necessary. For example, the effects of gravity have been reduced to zero for periods of less than 1 minute in aircraft flying Keplerian trajectories; subgravity states of longer duration have been achieved only in space vehicles. But even in the space flights of long duration astronauts have not yet experienced prolonged periods of free movement at zero gravity. For this condition, we make a less optimistic forecast, based upon recent analyses of sensorimotor function.

Humans and other mammals show a surprising lability in the responses of their sensorimotor systems. Both prolonged isolation of human observers in monotonous environments (sensory deprivation) and prolonged immobilization in relatively normal environments (motor deprivation) lead to degraded performance on perceptual-motor tasks (*1*). The young of primates and certain other mammals fail to develop normal visually guided behavior when they are deprived of contact with the sense-stimulating environment (*2*). On the more optimistic side, human subjects have shown remarkable ability to adapt to conditions of sensory rearrangement—for example, to the wearing of prisms over the eyes which produce displacement and distortion in the appearance of the visible world (*3*). These findings imply that the stability of man's spatial perception and spatially oriented behaviors depends upon habitual contact with the sense-stimulating environment. When such contact is reduced or otherwise altered for a considerable period, the human system for sensorimotor control reveals its plasticity. Technological advances are producing conditions—flight in space, in particular—which tax this system. They pose the practical problem of predicting conditions under which the coordination of the human operator may be degraded. In a broader context we should like to have a general theory of the plastic sensorimotor systems, one that would both specify the range of normal circumstances responsible for the development and maintenance of stability in behavior and explain lability under transformed conditions.

Motor-Sensory Feedback

Essential for the stability of many of the plastic systems is the order entailed in the relation between the natural movements of an individual in his environment and their consequent sensory feedback. When an observer moves with respect to the many objects in his everyday world, his view of them changes. Their images move on his retinas in a manner highly correlated with his movements. There is an analogous correlation in the hearing of sounds by a moving listener, and a similar relation exists when an individual both moves and views a part of his body. Under any one of these conditions, a given movement tends to cause a characteristic sensory feedback. The central nervous system of the observer is both the originator of the movement and the receiver of its consequent sensory feedback. The central nervous system may be assumed to retain information concerning the output signals and to be informed of the dependent input signals. Comparison between these signals serves as a means of discriminating between change of visual stimulation caused by moving objects and change of visual stimulation resulting from movement of the perceiving organism (*4, 5*). In addition, this information has an important function above and beyond its use in spatial discrimination. It is necessary for maintaining and for altering the response characteristics of the sensorimotor control system in humans and certain other higher mammals (*6*). Evidence in support of this assertion has come from the results of two complementary types of experiment: analytic studies of adaptation to sensory rearrangement and related experiments on the effects of depriving young mammals of contact with their normal environments.

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A rearrangement experiment with a human subject was first reported by Helmholtz, who viewed both his hand and other objects through a wedge prism (*7*). Because of the refraction of light, an object viewed through the prism appears displaced with respect to the position in which it would normally be seen by the naked eye. If the viewer reaches quickly for the object, he tends to miss it by an error equal to the optical displacement. However, as Helmholtz demonstrated, repeated efforts at reaching for the object result in compensation for this error and (equally important) in an error of the opposite direction upon removal of the prism.

To test the role of motor-sensory feedback in compensation for this classic form of rearrangement of eye-hand coordination, a procedure has been used as follows (*8*). During the period in which the subject viewed his hand through the prism (Fig. 1, *P*), his arm was strapped to a lever that pivoted around a bearing at his elbow, as shown in Fig. 1 (right). His head was held fixed by a bite board (not shown in Fig. 1). Under one condition of viewing ("active movement") he moved his arm back and forth through the field of view, to the beat of a metronome (30 cy/min), for several minutes. Under a second condition ("passive movement") he kept his arm limp while it was moved in the same manner and for the same period by an external force. Before, and again after, viewing his hand through the prism, the subject repeatedly marked the apparent locations of the virtual images (*T'* in Fig. 1). To him, these images of target points (*T*) appeared to lie on the surface under his hand when he saw them in the fully reflecting mirror (*M*). The mirror obscured both the subject's hand and his markings and consequently kept him from recognizing his errors. Comparisons made before and after the initiation of passive movement showed that the subject had not shifted the markings after periods of passive movement ranging up to half an hour. However, a few minutes of active movement produced substantial compensatory shifts, and many subjects showed complete compensation within half an hour after the initiation of active movement (*9*). Although the passive-movement condition provided the eye with the same optical information that the active-movement condition did, the crucial connection between motor output and visual feedback was lacking.

Other techniques, similar to this procedure for analyzing Helmholtz's experiment in terms of motor-sensory feedback, have been used to show the relevance of the movement condition for adaptation to many other types of rearrangement. To this end, Held and his collaborators have studied the effects of increasing the optical distance between hand and eye (*10*); of introducing locomotion during displacement of the visual field by wedge prisms (*11, 12*); of rotating the visual field by means of right-angled prisms (*13*); of inducing intrafield distortions by means of flat wedge prisms (*14*); and of "displacing the ears" to new positions with respect to the head by means of electronic pseudophones (*15*). In any of these rearrangements, the subject initially makes an error, in either a localizing response or a measure of spatial perception, that is predictable from the magnitude of the imposed displacement or distortion. However, in accord with our findings in the experiment described, if he is allowed free movement either of his whole body, as in locomotion, or of an appropriate limb, he will compensate for the initially induced error. If restrictions are placed on his movements or if parts of his body are moved by an external force in such a way that the variation in sensory stimulation is equivalent to that received with free movement, there is no comparable adaptation. Some adaptation may be produced by factors other than motor-sensory feedback. But such factors, insofar as their effects have been explored, seem to lead to changes that are limited as compared to the full and exact compensation that can be demonstrated on sufficiently long exposure to conditions of rearrangement accompanied by free movement (*9, 11–13, 15*).

Demonstration of complete compensation is of crucial importance in bridging the gap between adaptation in the adult and original development in the newborn infant. When it can be shown that adaptation proceeds to a stable end state which corresponds to accurate orientation in the environment, then it is conceivable that the same process operates in the development of coordination in the newborn infant. A recent study has in fact demonstrated the importance of motor-sensory feedback for the course of visual development from birth. The research was suggested by work of Riesen and his collaborators (*2*), who had previously demonstrated deficits in the visually-guided behaviors of cats and a chimpanzee reared from birth under conditions of restricted mobility when in the light. Following this lead, Held and Hein reared paired kittens under conditions such that, when the animals were in the light, only one of them was allowed to move about, the other being transported over an almost identical path (*16*). By this means the two kittens were provided with equivalent visual stimulation. The results showed that the kitten which was transported failed, in contrast to its actively moving mate, to develop normal visual-spatial capacities, despite its exposure to the patterned and varied visual surround. From these findings we conclude that the information entailed in the motor-sensory feedback loop allows the sensorimotor system both to set (as in development) and to reset (as in adaptation to rearrangement) its response characteristics as a consequence of its own past actions.

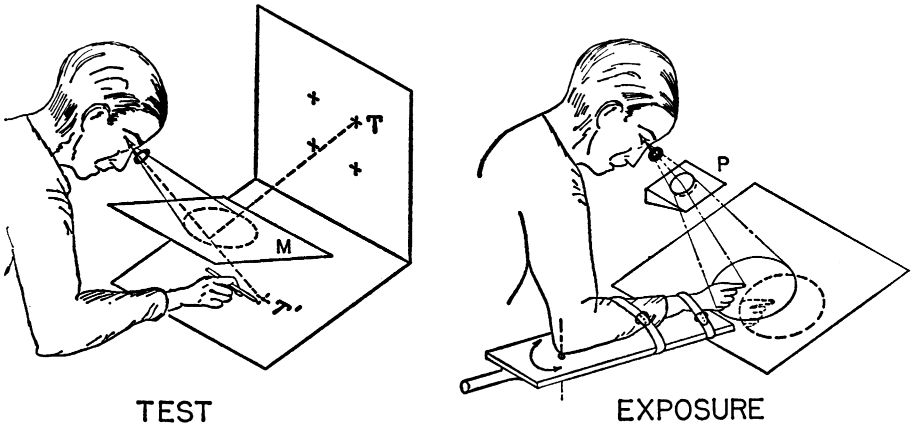


Fig. 1. Apparatus for rearranging eye-hand coordination and for testing the consequences of such rearrangement.

Motor-Sensory Correlation

The crucial role of natural movement in adaptation to rearrangement and in the development of the newborn infant hints at the importance of the correlation between motor output and sensory feedback signals. How is this factor implicated? For an answer, we must look more closely at the normal relation between movement and sensory feedback and at the effects of transforms of this relation.

In the case of eye-hand coordination, the geometry of movement specifies that each distinguishably different movement of the hand will be accompanied by a unique change in the viewer's image of that hand, provided that variations in the positions of eye and head are discounted. If these variations are not discounted, the function that relates movement of the arm and hand to its visual feedback will contain parameters whose values specify different positions of the eye and head. Information concerning these positions—hence the values of the parameters—is available to the nervous system. For any set of parameter values, viewing the hand entails a one-to-one relation between movement and visual feedback. During the course of a large number of movements the nervous system may take account of the internally initiated efferent signals to the musculature, together with their concurrent visual feedback. Within the limits of precision afforded by the transfer of information within the neuromuscular system, the one-to-one relation between movement and its sensory feedback will allow the system to establish and store the correlated information. When, as in the experiment described, the hand is viewed through a wedge prism, it is displaced from the normal position by a fixed distance. Although any particular movement is now accompanied by a different feedback, the one-to-one relation between movement and sensory feedback is preserved. During the course of further movements of the arm and hand, the newly correlated information becomes available to the nervous system. This invariant order is, we believe, responsible for adaptation to the prism transform.

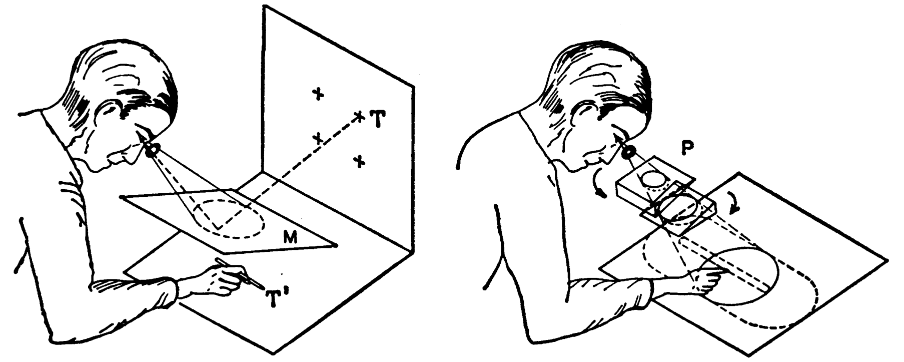
Full compensation for the errors in visual direction (egocentric localization) induced by a wedge prism appears to require gross movement of the head and eyes in a patterned and visible surround (*11, 12*). These movements make the analysis of the relation between motor output and sensory input more complicated than is the case for eye-hand coordination. Let us consider a bodily movement which transports the eye through an environment containing stationary objects. The initial position and subsequent displacement of the eye geometrically determine certain properties of the ensuing stimulation of the retina of that eye—those that Gibson has called the "flow patterns" (*17*). When the eye rotates about an axis through its center (its nodal point, to be exact), all imaged points move across the retina at the velocity of rotation of the eye. When the eye translates toward an external point that casts its image on the retina, all other imaged points move radially outward from this central image point originating on the line of translation. For every different direction of translation, the center of radial flow is different. There is, then, a one-to-one relation between the directions of translational movement and the corresponding centers of flow patterns on the retina.

A wedge prism, fixed in its position with respect to the eye, shifts the center of flow normally characteristic of any given translational movement by an amount equal to the prism-induced displacement of the central image point. The one-to-one relation between direction of translation and center of flow pattern is maintained. The prism transform is isomorphic with respect to this relation, a condition that we believe is consistent with the observation that translational movements of the eye are required for complete compensation of the errors in direction-finding induced in a subject by wearing a wedge prism (*11, 12*).

The foregoing considerations apply to the movements of a disembodied eye. However, translational movements of the eye are naturally produced by movements of the head, trunk, and limbs. Movement of the eye is mediated through the various linkages that connect it to these parts of the body. Rotational displacements of the eye, however produced, can change the relation between translational movements, as normally produced, and their consequent visual feedback. The function relating translational movement to visual feedback then contains parameters which have different values for each set of states of the various linkages responsible for rotations of the eye. Information about the positions of these linked parts must be available to the central nervous system if the effects of rotation are to be factored out.

Fixed displacements of the "ears" around the cephalocaudal axis of the head, produced by means of pseudophones, transform the relations between translational movements of the head and binaural acoustic signals in a manner analogous to the changing of the relations between head movements and visual signals by a wedge prism. Although the pairing of directions of translation and particular sequences of auditory stimulation is changed, the one-to-one relation between members of these pairs is preserved. As in visual direction-finding, rotational displacements of the head must be represented by parameters of the function relating translational movement and auditory feedback.

Full and exact adaptation to a rearrangement represents a change in state of the relevant sensorimotor control system such that the input-output or stimulus-response relation becomes identical to that which existed prior to rearrangement. In accord with analyses of the type discussed earlier, we believe that this change in state is dependent, in the first instance, upon an invariance of relations in the functions describing movement with its consequent sensory feedback. The invariance is entailed in idealized geometrical and physical descriptions of the effects of rearrangement. These descriptions, together with several assumptions, account for the availability of ordered information to the nervous system. On the motor side, the system must be informed of its own output and of the changes in linkages that set the values of parameters in the feedback loop. The precision of transfer of information in the neural route between the origin of efferent signals and the muscular output sets limitations. Similar limitations exist on the sensory side. Observations of the precision of normal sensorimotor coordinations strongly suggest that these limitations are not severe. In any event, to the extent that these transfer functions are stable in time, repetitions of specific efferent signals may, subject to certain considerations that are discussed later, be accompanied by characteristic sensory feedback signals [called "reafferent signals" by von Holst (*4*)]. Over time, the cumulated set of paired efferent and reafferent signals should, then, show a high correlation. The correlated information is, we believe, necessary for the



TEST

EXPOSURE

Fig. 2. Apparatus for disarranging eye-hand coordination and for testing the consequences of such disarrangement.

development and maintenance of the plastic coordinations under normal conditions and for their adaptability to the transforms produced by rearrangement.

Decorrelated Feedback

In asserting that reafferent stimulation is predictable from bodily movement in general, and is related in one-to-one fashion to certain components of movement, we made two presuppositions about physical aspects of the interaction between organism and environment. (i) We assumed that the observer moves in a world well populated with stationary sources of stimulation. (ii) We assumed that output (efferent) signals in the central nervous system and their consequent muscular contractions produce the same bodily movements on all occasions. In other words, the exertion of force by muscular contraction was assumed to yield consistently predictable movements of the body and its parts. Under normal conditions of terrestrial life, including those that obtain during most rearrangement experiments, both of these assumptions are tenable. The visible world, for example, is crowded with objects of which a great proportion are stationary. Bodily movements are, for the most part, the resultants of muscular exertion against the counterforces of objects and gravity. Frictional forces generated by contact with objects strongly dampen these movements and inhibit ballistic motion. Muscular exertion, then, normally does produce corresponding bodily movement. Taken together, these physical conditions entail the redundant information required for the establishment of the correlation of signals discussed earlier. An exception can occur when the body or any of its parts is prevented from making contact with external objects. Muscular contraction may then be unrelated to certain aspects of bodily movement. But such exceptions are rare. Men do not fly through the air, unsupported, for any appreciable length of time. The strongest impulse that can be generated by the human musculature is insufficient to keep a man's body in the air and out of contact with objects for more than a fraction of a second. Even the trampoline artist does not remain in the air longer than about 1½ seconds. Consequently, we can normally expect a high order of predictability, that is invariant over time, in the relation between particular efferent and reafferent signals in the nervous system. However, either one or both of our presuppositions may become untenable in extraterrestrial environments.

Consider, for example, the astronaut in free flight. If he is not strapped down but is free to push on objects, the consequent displacement of his body will be limited only by renewed contact with obstructions. During this ballistic movement, muscular effort may produce movement of parts of the body around its center of mass but will not change the trajectory of this center. The result may be a radical change from the high correlation between motor output signals and their sensory consequences that is experienced on earth. In the absence of specially imposed constraints, the relation between motor output and accompanying sensory input may vary, over time, in a very complex manner. The same consequence would be produced if the normal environment were to be replaced by one of continuously shifting visible objects, such as are seen on a "noisy" television screen. We have speculated elsewhere (*6*) that this condition may be approximated by a blank visual field which allows noise intrinsic to the visual nervous system to become the dominant signal. Prolonged exposure to either a blank or a noisy visual field (sensory deprivation) alters spatial perception and coordination. But can we suggest an analog to the astronaut's condition that is less speculative—one that can lead to terrestrial experiments?

A rearrangement such as is effected either by placing wedge prisms before the eyes or by using pseudophones transforms the relation between motor output and sensory feedback in an isomorphic, continuous, and time-independent manner. Exposure in the normal environment leads to adaptation to the rearranged condition, with its corollary of temporary maladaptation upon return to the former, nonrearranged state. Suppose, however, we introduce a time-varying factor into the external circuit of the feedback loop—one over which the central nervous system has no control. This is, in principle, the condition to which our floating astronaut is exposed. The normal relation between certain efferent and reafferent signals may then become more complex and even unpredictable. In time, the cumulated pairs of signals should show a reduced correlation. Considerations such as those we have discussed led us to suspect that in time the state of the system might be changed so as to produce increased ambiguity of response to relevant sensory signals. For convenience, we have termed the imposed condition "disarrangement," in contradistinction to rearrangement (see *11*). We have performed disarrangement experiments in both visual and auditory domains to learn the consequences of such time-varying transforms in the motor-sensory feedback loop.

Visual-Motor Disarrangement

Because of its great lability, the system for eye-hand coordination lends itself to rapid testing of the consequence of introducing a time-varying parameter. For the purpose, a prism of variable power P was introduced between eye and hand in the course of the experiment, as shown schematically in Fig. 2 (right). Actually, the subject had in front of each eye a rotary prism consisting of two wedge-shaped elements of equal power that rotated at equal speeds but in opposite directions around the line of sight. The prisms were coupled together so that their powers could be maintained equal and no large binocular differences would be introduced. The device produced a continually varying displacement of the seen location of the subject's hand—a displacement independent of the movements of the hand itself. The displacement was cyclical, ranging equally to the left and right and back along the effective base-apex axis of the prism, at 1 cycle per minute. The axis could readily be changed so that the displacements occurred in the up-down direction. Measurements of eye-hand coordination were made before and after the periods of time-varying displacement in order to assess the effects of the displacement. The measurements were made in the apparatus shown in Fig. 2 (left). The test procedure was identical to that described in connection with Fig. 1 (left).

Figure 3 shows the markings made by one subject in two separate 64-minute sessions in which either up-down or right-left displacement was produced by a prism of varying power (maximum, 40 diopters). This subject had been instructed to move his forearm and hand back and forth over a small arc while he viewed it through the prisms. The most apparent change in the markings after introduction of the rotary prism was an increase in the dispersion of the markings along the dimension of optical displacement induced by the prisms. These markings show significant changes neither in dispersion at right angles to the induced displacement nor in the mean positions (centroids) of the group of marks. Furthermore, observations of successive markings revealed no tendency toward cyclical variation of position such as might be produced if the periodicity of the displacement cycle had somehow been learned by the subject.

The reduction of accuracy in eye-hand coordination implies that the control system has been degraded in the dimension specific to the time-varying parameter. This specificity affords an experimental control for testing the possibility that the increase in the dispersion of marks might result from fatigue alone, since such an effect should not be restricted to one dimension. The result is consistent with expectations derived from the considerations discussed, but it suggests the more stringent test in which results obtained under conditions of active and passive movement are contrasted. The basic findings prompted us to perform several experiments (*18*), of which the following is a representative sample.

Tests were made with eight undergraduates, two male and six female. Each subject was tested under four different experimental conditions, the order of the four tests being different for each subject. Two base settings of a variable prism with maximum power of 30 diopters were used: the effective base-apex axis (equivalent to the direction of optical displacement) was set at either the right-left (*R–L*) or the up-down (*U–D*) position. Each of the two prism settings was combined with either an active or a passive movement of the arm. To insure that movements of the arm and hand were equivalent, and hence gave equivalent visual information to the eye under all viewing conditions, the subject was allowed to move his arm only in accordance with the procedure described for Fig. 1. Test markings were made before exposure to the conditions of the experiment and 8, 16, 32, 48, and 64 minutes, respectively, after the beginning of such exposure.

The averaged percentage increases in the standard deviations of the markings for all subjects under all conditions are shown in the semilog plots of Fig. 4. The standard deviations were calculated separately for the *R–L* and *U–D* dimensions. From these graphs it is apparent that the dispersion of markings increased along the dimension of variation during viewing with active movement but not during viewing with passive movement. The passive-movement condition yielded no significant increase in dispersion along the dimension of variation, and the increase that occurs along the *R–L* dimension under the condition of *U–D* setting and passive movement appears to be unrelated to duration of exposure to the testing conditions. Statistical tests of the changes in dispersion after 64 minutes of exposure showed that the two base settings of the prism and the active-movement, as opposed to the passive-movement, condition had significant effects (*19*).

Auditory-Motor Disarrangement

The separation of the two "ears" results in detectable binaural differences in the time, phase, and intensity of the sound coming from any localized sound source. Although localization of the source is possible without movement, the listener will ordinarily move his head or his whole body in relation to the sound source for greater accuracy. We tend to turn our faces in

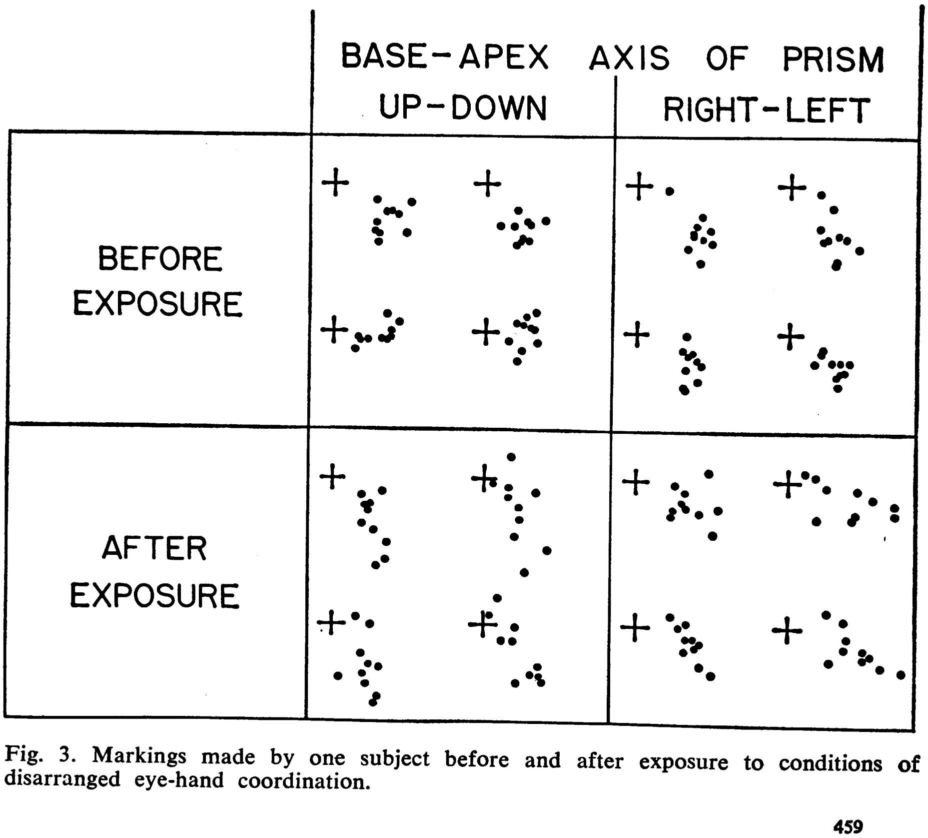


Fig. 3. Markings made by one subject before and after exposure to conditions of disarranged eye-hand coordination.

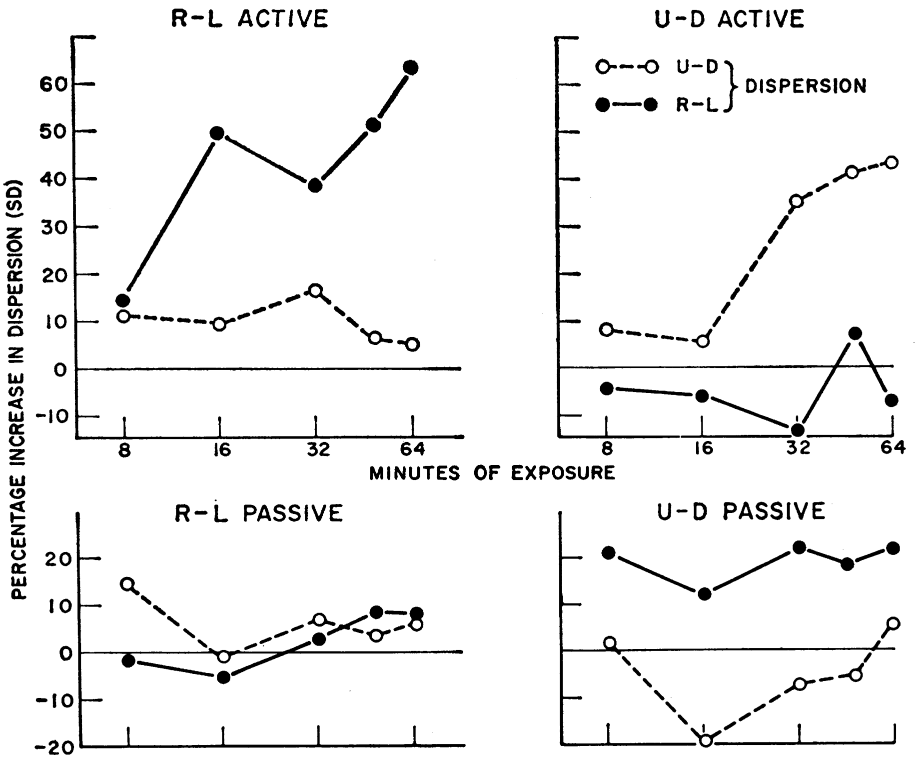


Fig. 4. Effect of exposure to conditions of disarranged eye-hand coordination in connection with active and passive movement, with right-left (*R–L*) and up-down (*U–D*) orientations of the base-apex axis of the prism.

the direction of one of two telephones to make sure which one is ringing. We rotate the head until there are no differences in the sound as detected by the two ears. This "nulling" is possible only because the listener's movement produces systematic changes in the binaural differences (*20*). The use of this correlated motor-sensory information in auditory discrimination is analogous to its use in visual-spatial discrimination. And, as in the case of vision, the same information is responsible for adaptation to rearrangement (*15*). Consequently, the introduction of a time-varying parameter into the motor-sensory feedback loop should have an effect similar to that described for visual-motor disarrangement.

Discrimination of dichotic time difference (the difference in time of arrival at the two ears of corresponding acoustic signals) was chosen as the criterion task because of its importance in auditory direction-finding. Subjects were exposed to white noise, from separate but equivalent sources, which stimulated the two ears under various conditions of motility. This stimulation produces rapidly changing dichotic time differences whose temporal distribution is complex and unrelated to the actions of the subject. During an extended period of such exposure a variety of time differences will occur simultaneously with any particular movement made by the subject. The efferent-reafferent correlation should thus be reduced, with consequent loss of accuracy in localization.

To test the importance of motility in the expected degradation of the ability to discriminate dichotic time difference, 12 male college students were used as subjects. They were trained to a stable level of performance in the discrimination task and were then exposed for 2 hours to continuous stereophonic white noise under different conditions of movement. The subjects were tested before exposure and after 1 and 2 hours of exposure, by means of a procedure described in detail elsewhere (*21*). Briefly, it was as follows. The subject reported the apparent lateral direction (left or right) of paired clicks delivered to opposite ears with small but varied time differences. The set of thresholds of discrimination of change in the apparent direction of the clicks provided a measure of variability. The question may be raised as to whether localization of the apparent source of sounds coming to the ears by way of earphones is equivalent to localization of an external sound source. Jeffress and Taylor, in a recent study (*22*), demonstrated that there are no essential differences, and they claim that the two tasks involve identical processes.

The principal comparison made was between results of sessions in which subjects walked up and down a busy corridor during exposure to the white noise and sessions during which they lay relatively motionless on a bed. After exposure to the ambulatory condition, the subjects' ability to discriminate minute differences in the time of arrival of the sound at the two ears deteriorated very significantly. The mean variability of judgments (standard deviations) increased 104 percent after 1 hour, and then declined to 79 after 2 hours, of exposure. On the other hand, the subjects' performance did not deteriorate when bodily movements were restricted; mean variability decreased 2 percent after 1 hour, and 5 percent after 2 hours, of exposure (*23*).

Using the techniques described, Freedman and Secunda (*24*) attempted to analyze the particular components of gross bodily movement which are responsible for the deterioration in performance during exposure to this auditory disarrangement. They found that (i) either rotation of the whole body or simple rotation of the head, without translation, during exposure to dichotic white noise led to deterioration in discrimination not significantly different from that produced with free ambulation; (ii) the effect occurred reliably within 1 hour; (iii) full recovery after exposure occurred within half an hour.

These results are all consistent with the effects of exposure to decorrelated feedback. They led us to make further experiments to compare the effects on auditory discrimination of active and passive movement.

Having isolated rotation as a condition sufficient to produce the auditory effects previously measured, we have been able to make separate experiments to compare the effects of the active and passive conditions for either rotational or translational movement. In the active-rotation condition the subject turned his head back and forth around a fixed cephalocaudal axis in a timed sequence of movements. In the passive-rotation condition he sat in a chair on a swiveled platform which was rotated by the experimenter through the same sequence.

In the translational-movement condition he either walked or was transported in a wheel chair up and down a long corridor. In all conditions he wore earphones producing white noise. As in the visual-motor experiments, passive movement did not produce significant changes in performance during long exposure (1 hour); active movement was necessary for the degrading effect (*25*). After active movement, either rotational or translational, the variability (standard deviation) of judgments increased 41 percent; after passive rotational movement the variability increased 1 percent; after passive translational movement it decreased 5 percent.

Discussion

Prolonged exposure to conditions of decorrelated feedback clearly degrades the accuracy of response in both of the sensorimotor coordinations that have been studied. The differential effect of active movement as opposed to passive movement (or to no movement) is striking. In the absence of active movement, degradation does not occur. To the extent that an astronaut is exposed to decorrelated feedback, degraded performance on relevant tasks can be expected. Such losses may be prevented—and perhaps have been—by restricting bodily movement during exposures that entail the physical changes responsible for decorrelation.

Self-produced bodily movement, with its concurrent sensory feedback, provides an order required for organizing and reorganizing plastic sensorimotor systems. The experimental techniques of rearrangement and disarrangement have been used to perturb these systems. They have revealed some of the conditions that determine the response characteristics of the systems. These findings have a bearing on original development, as well as on the maintenance of behavioral capacities in higher mammals. We can understand the plasticity of these systems by thinking of them as having built-in programs that will produce precise sensorimotor coordination provided certain quasi-constant values have been set by information available from the motor-sensory feedback loop. Normal contact with the environment provides the highly correlated information that sets close bounds to the range of values of these constants. Contact during rearrangement alters the values of the constants but does not change the range of their variation. However, any condition that tends to disorder and decorrelate the information entailed in the relation that normally exists between motor output and contingent sensory input will increase the range of values of some constants and yield the degrading effect shown experimentally.

Both adaptation and degradation can be defined in the terms discussed. The adaptation of the sensorimotor system is optimal when the constants are not significantly different from those currently inferable from the transfer of information through the motor-sensory loop. The adaptation will be less than optimal to the extent that this condition is not met. Since a history of exposure sets the values of the program constants, adaptation inevitably lags behind transforms in the loop. From this point of view, the increasingly variable responses produced by exposure to a time-varying transform in the loop represent an adaptive trend. The increasing range of values of the program constants is made evident by degraded coordination in tests carried out under stable conditions, which, in our experiments, are represented by the measuring conditions.

This discussion reflects the truism that an organism's adaptation is related to the regularities of its world. Perhaps less obvious is our conclusion that the stimulus transforms that accompany the movement of an organism are an important source of order in adaptation. This order is, in turn, dependent upon the quasi-constancy of several physical factors, among which is gravitation. In the absence of one or another of these factors, coordinations which depend upon their regularizing influence will, in time, be lost.

Summary

The maintenance and development of sensorily guided behavior depend in part upon bodily movement in the normal environment. Ordered information entailed in the motor-sensory feedback loop is responsible for the stable functioning of the plastic systems of coordination. It is found, from the results of experiments on vision and hearing, that the introduction of disorder into the motor-sensory loop changes the state of these systems and makes performance imprecise. In space, a freely moving astronaut will be exposed to a condition analogous to that of the subjects of these experiments. Consequently, he may lose his ability to perform certain tasks requiring precise sensorimotor control (*26*).

References and Notes

1. D. W. Fiske, in *Functions of Varied Experience*, D. W. Fiske and S. R. Maddi, Eds. (Dorsey, Homewood, Ill., 1961), pp. 106–144; J. P. Zubek, M. Aftanas, K. Kovach, L. Wilgosh, G. Winocur, *Can. J. Psychol.* **17**, 118 (1963).
2. A. H. Riesen, in *Biological and Biochemical Bases of Behavior*, H. F. Harlow and C. N. Woolsey, Eds. (Univ. of Wisconsin Press, Madison, 1958), pp. 425–450.
3. A short review of such experiments can be found in H.-L. Teuber, *Handbook of Physiology*, Sect. 1, *Neurophysiology*, J. Field, H. W. Magoun, V. E. Hall, Eds. (American Physiological Society, Washington D.C., 1960), vol. 3, pp. 1634–1638; the most spectacular examples of adaptation to rearrangement are presented in I. Kohler, *"Ueber Aufbau und Wandlungen der Wahrnehmungswelt," Sitzuber. Oesterr. Akad. Wiss., Kl. Phil. Hist.* **1951**, 1 (1951). A review of selected studies appears in K. U. Smith and W. M. Smith, *Perception and Motion* (Saunders, Philadelphia, 1962).
4. E. von Holst, *Studium Generale* **10**, 231 (1957).
5. D. M. MacKay has raised rather fundamental objections to von Holst's explanation and has proposed a more plausible model in *Aspects of the Theory of Artificial Intelligence*, C. A. Muses, Ed. (Plenum, New York, 1962), pp. 83–103.
6. R. Held, *J. Nervous Mental Disease* **132**, 26 (1961); A. Hein and R. Held, in *Biological Prototypes and Synthetic Systems*, E. E. Bernard and M. R. Kare, Eds. (Plenum, New York, 1962), vol. 1, pp. 71–74.
7. H. von Helmholtz, *Handbuch der physiologischen Optik* (Voss, Leipzig, 1867), vol. 1, pp. 601–602.
8. R. Held and N. Gottlieb, *Perceptual Motor Skills* **8**, 83 (1958); R. Held and A. Hein, *ibid.* p. 87.
9. A. Hein and R. Held, paper presented at Eastern Psychological Association meeting, Philadelphia, 1958.
10. R. Held and M. Schlank, *Am. J. Psychol.* **72**, 603 (1959).
11. R. Held and J. Bossom, *J. Comp. Physiol. Psychol.* **54**, 33 (1961).
12. J. Bossom and R. Held, *Am. Psychologist* **14**, 436 (1959) (abstract).
13. R. Held, *Psychologische Beitr.* **6**, 439 (1962); H. Mikaelian and R. Held, *Am. J. Psychol.*, in press.
14. R. Held and J. Rekosh, *Science* **141**, 722 (1963).
15. R. Held, *Am. Psychologist* **7**, 262 (1952) (abstract); *Am. J. Psychol.* **68**, 526 (1955).
16. ——— and A. Hein, *J. Comp. Physiol. Psychol.*, in press.
17. J. J. Gibson, *Brit. J. Psychol.* **49**, 182 (1958).
18. M. Cohen and R. Held, paper presented at Eastern Psychological Association meeting, New York, 1960.
19. A three-way analysis of variance (subject × prism base setting × active-passive) was performed on the mean changes of the difference between horizontal and vertical dispersion after 64 minutes of exposure. *F* for prism base setting was significant beyond the .01 level; *F* for the interaction between prism base setting and the passive-active dimension was significant beyond the .05 level.
20. H. Wallach, *J. Exptl. Psychol.* **27**, 339 (1940).
21. S. J. Freedman and D. W. Pfaff, *J. Audit. Res.* **2**, 305 (1962); *U.S. Air Force Office of Scientific Research Tech. Rept. AFOSR-503* (1961).
22. L. A. Jeffress and R. W. Taylor, *J. Acoust. Soc. Am.* **33**, 482 (1961).
23. The difference between these two experimental conditions was significant at better

than $p = .005$, as determined by the Wilcoxon matched-pairs signed-ranks test. In addition, a Friedman two-way analysis of variance showed the conditions to be the significant variable $(p = .005)$.

24. S. J. Freedman and S. Secunda, paper presented at Eastern Psychological Association meeting, Atlantic City, 1962; *U.S. Air Force Office of Scientific Research Tech. Rept. AFOSR-2078* (1962).
25. J. Zacks and S. Freedman, paper presented at Eastern Psychological Association meeting, New York, 1963.
26. The program of research in visual-motor coordination on which this article is based was supported by the National Institute of Mental Health (grant M-3657) and the National Science Foundation. The work owes much to the assistance of Harry Cohen, Malcolm Cohen, Jack Glick, and especially Aglaia Efstathiou. The research in audition has been supported by grants from the U.S. Air Force Office of Scientific Research to Dr. Freedman (currently, by grant AF-AFOSR 53-63). The research in visual-motor coordination is being continued at Massachusetts Institute of Technology under the support of the National Institute of Mental Health (grant M-7642), the U.S. Air Force Office of Scientific Research (grant AF-AFOSR 354-63), the National Aeronautics and Space Administration (grant NSG-496), and the Rockefeller Foundation.

National Goals and the University

We face a dilemma that calls for a careful rethinking of national policy and university functions.

J. C. Warner

I want to take this opportunity to express some concerns about colleges and universities, about the people who administer them, and about the people who teach and do scholarly work in them.

These concerns have their origin in the fact that our universities and the people in them are being used, in this period since World War II, as instruments of national policy at home and abroad. National policy requires that we solve the necessary problems to attain two major goals: (i) to maintain or improve our position in the scientific, technological, economic, ideological race with the Soviet Union; (ii) to maintain our democratic institutions and a sound economy at home.

The first of these goals appears to mean a number of things: (i) providing and maintaining a military capability which is adequate to insure our defense and security and is never permitted to become obsolete; (ii) providing financial and technical aid for improving agriculture, industry, and education in uncommitted but underdeveloped countries; and (iii) maintaining a position of national prestige in such things as space exploration, space travel, high-energy physics, and the peaceful uses of fission and thermonuclear energy.

The second goal means a number of things: (i) preventing a rapid rate of inflation; (ii) maintaining such a rate of economic growth as will further improve our standard of living and will provide full employment; and (iii) providing the educational opportunities desired by our expanding population and necessary to the attainment of our other national goals.

I presume Americans are almost unanimous in support of the national goals I have mentioned. They are less than unanimous about the things which are essential to attain these goals, and they are far from unanimous, oftentimes acrimonious, when it comes to setting priorities or making choices among activities and enterprises which compete for dollars and for our most competent manpower.

In all of this the universities have found themselves "in the middle" because the various urgent demands made upon them and their people are often mutually inconsistent and often are of such nature that they force the university community to depart from its proper role in society, the role in which it is best qualified to serve society.

At the same time that the colleges and universities are being required to provide higher education for twice as many young men and women, to produce twice as many scholars and professional people educated to high levels of competence in their graduate and professional schools, and to undertake very substantial research programs for government departments and agencies, the government is calling upon the universities to give full-time leave to a very large number of their best people so that they may serve in government posts at home or in the multitude of foreign-aid projects which we support in the underdeveloped countries. And the government is calling upon the universities to give a host of others part-time leave to serve on advisory committees and panels too numerous to mention. This has thrown the colleges and universities into such strenuous competition for talent that any university determined to maintain the quality of its programs finds its educational costs rising a good bit faster than the price level, even when size is maintained constant. That the colleges and universities are faced with a financial problem of great magnitude is obvious. Higher education now costs us about \$4.5 billion annually. By 1972 we are supposed to double our enrollments. Thus, costs may be expected to rise to about \$9 billion because of size alone. If one includes even a conservative factor for inflation and the highly competitive market for faculty, the bill most certainly will be \$11 or \$12 billion by the 1970's.

The more fundamental problem (and I worry about it more than the money problem), both for the universities and the nation, is the competition that has been engendered for the very highly trained and creative individuals who comprise the faculties of our universities. How this precious talent is used will probably be the most important single determinant of whether or not we shall achieve our national objectives in the long run. It is a question too important to be decided on the basis of short-term propaganda victories; it is a question to which the

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