Adaptation to rearranged eye-foot coordination

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The generality of adaptation following three types of movements during prism exposure was investigated. The three exposure conditions consisted of (1) walking with prisms, (2) viewing leg movements through prisms, and (3) viewing arm movements through prisms. The results showed that changes in eye-foot coordination and egocentric localization occur following both (1) and (2). Exposure Conditions 2 and 3 both produce changes in eye-hand coordination; however, eye-foot coordination was found unaltered following (3).

The source of reafference during exposure to prism rearrangement determines the extent to which sensorimotor adaptation generalizes (Held & Hein, 1960; Mikaelian, 1967). Movements of the arm viewed through prisms generate adaptive changes confined to responses with that arm, while walking with prisms produces changes in responses entailing the arm (not viewed during exposure) as well as the body, e.g., egocentric localizations.

Systematic variation in prism adaptation, following different types of movements, has led to several speculations about its underlying processes. The model proposed by Held defines adaptation to rearrangement as the "formation of new relationships between centrally controlled movements and spatial orientation of different parts of the body [Hein, 1966]." Exposure to sensory distortion produces a remapping or recalibration of directed movements of limbs upon target-oriented directions of the head. Arm movements viewed through prisms recalibrate directed movements of the arm with respect to head orientation, and walking with prisms introduces a shift in target-oriented directions of the head. In the former case, sensorimotor changes are generally confined to eye-hand coordinations, while in the latter equivalent changes occur in target-oriented directional movements of limbs and/or head.

Movements and sensorimotor tests in most adaptation studies have used either the arm or the head-body (Rock, 1966; Howard & Templeton, 1965). Hamilton (1964) has published the only systematic eye-leg rearrangement study in which Ss reached for targets with their feet while viewing through prisms. His results show that this type of exposure to rearrangement alters responses with the whole body (walking towards a visual target), as well as limb responses (pointing with arms or foot). Unlike arm movements, leg movements viewed through prisms change responses entailing that limb as well as other limbs or the whole body. In terms of Held's model (Held & Freedman, 1963), target-oriented head directions shift following prism-viewed movements of the leg, a situation thought to occur only with prolonged walking with prisms.

The similarity of adaptation produced by leg movements to that produced by walking led to the present series of studies on adaptation to rearranged eye-foot coordination. These experiments were designed to examine Hamilton's observations on changes in eye-hand, eye-foot, and eye-body coordination following the viewing of leg movements through prisms. A second aim was to investigate changes in these responses following (1) prism viewing of arm movements, and (2) walking with prisms (legs out of view). The methods used allowed direct comparison of results with those of earlier studies.

Hamilton's Ss were exposed to rearrangement lying down in the exposure apparatus. They were tested for adaptation either by pointing to targets (with arm or foot) in this position, or walking towards visual targets with eyes closed (after having first located the target visually). While one can accurately measure errors in pointing, it is difficult to measure correctly and reliably changes in direction of walking, with eyes closed, towards a target. The exposure and test apparatus used in this experiment were designed to avoid this problem and to facilitate exposure.

METHOD

Subjects

Eight right-handed college students with normal vision were used.

Apparatus

Exposure apparatus. To allow S to view the movements of his arm or leg using the same apparatus, prism goggles were mounted over a rectangular opening on a slanted table top. The lower end of the slant was at S's shoulder level, enabling him, seated on a stool, to rest his head comfortably on the goggles. A removable horizontal opaque surface under the table top and several inches above S's lap provided the field in which arm movements were viewed without sight of the legs. For viewing leg movements the opaque surface was removed, allowing S to see several inches above his knee. He rested his arms

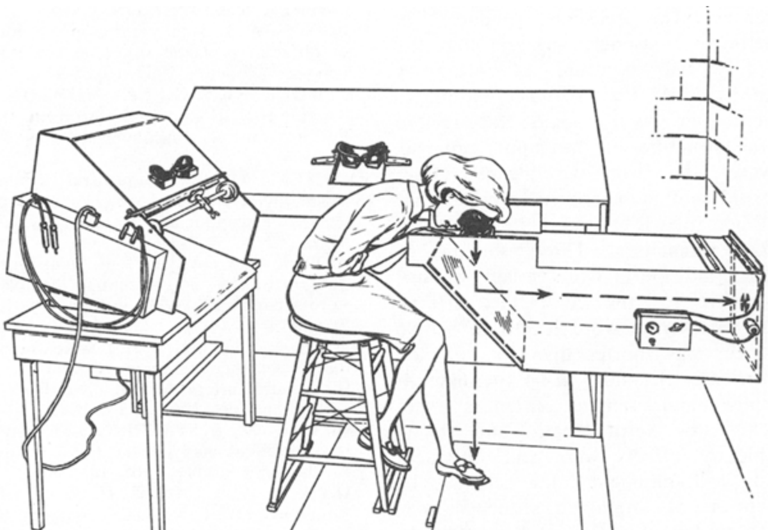

Fig. 1. Eye-hand and eye-foot coordination test apparatus and exposure table.

on the table surface while moving his leg from side to side under it. Use of goggles rigidly attached to the table reduced head movements to a minimum during exposure.

Test apparatus. Three types of sensorimotor coordination tests were used: eye-hand coordination, eye-foot coordination, and egocentric localization. The test apparatus for these, along with the exposure apparatus (Fig. 1, egocentric apparatus not shown), were located close to each other. S could be tested for eye-foot and eye-hand coordination without getting up, and took only one step to get into the egocentric localization apparatus.

(a) *Eye-hand coordination.* A Held-Gottlieb (1958) type of eye-hand coordination box was used. It enabled S to mark with his hand the location of the virtual image of targets viewed in a fully reflecting mirror. The apparatus allowed binocular viewing of a mirror which, at 45 deg to the plane of the targets, cast the virtual image onto a horizontal surface upon which S marked the perceived location of the targets. The mirror obscured both the S's hand and his markings and consequently kept him from recognizing his errors. Using his right hand (and a biteboard to reduce head movements) S marked the location of the virtual image of four targets 10 times, presented singly in a random order, for a total of 40 markings. He moved his hand out of the test box after each marking to eliminate motor set.

(b) *Eye-foot coordination.* The test apparatus used the same principle as that employed in the eye-hand coordination test box, except that the distance between target and mirror was increased to project the virtual image of the targets on the plane of the floor. S, resting his head over goggles on the test box, marked the location of the virtual image of a target with a stylus attached to his shoe (right foot). Each of four targets, presented singly in a random order, was marked eight times for a total of 32 markings.

(c) *Egocentric localization.* A full description of the apparatus appears elsewhere (Mikaelian & Held, 1964). It essentially consists of a rotating chair with appropriate scales to measure the S's orientation in relation to a visual target. In practice, a visual target (a slit of light ¼ x 4 in.), which could be placed in any position around S in an otherwise darkened room, was stationed in one of the five preselected locations. The target light was turned on and S rotated himself left or right to bring the target straight ahead of him. Each target orientation was approached from a clockwise and counterclockwise direction resulting in a total of 10 egocentric localizations. Head movements were reduced with a biteboard rigidly attached to the rotating chair, and empty goggles were worn during testing to match the facial tactile stimulus condition experienced during exposure due to prism goggles. The difference between subjective and objective straight ahead was the recorded "error" measurement.

Table 1

Changes, in Degrees of Visual Angle, in Sensorimotor Responding Following 50 Min of Active Exposure to Rearrangement; Binocular, Prisms Base Left, 10 Deg Lateral Displacement

Exposure Condition	Walking with Prisms		Viewing Leg Movements (Eye-Foot Exposure)	
Test Subjects	Egocentric Localization	Eye-Foot Coordination	Egocentric Localization	Eye-Foot Coordination
1	1.1	3.8	2.1	7.2
2	4.3	3.8	3.7	6.1
3	2.5	3.0	1.8	4.9
4	1.8	3.8	5.3	8.2
5	2.3	6.3	2.1	5.1
6	3.3	1.7	0.8	7.2
7	1.1	1.5	1.0	4.2
8	2.8	5.4	3.0	5.1
Mean	2.4	3.6	2.5	6.0
Per Cent Adaptation	24	36	25	60
P (t-test)	<0.001	<0.001	<0.01	<0.001

Table 2

Changes, in Degrees of Visual Angle, in Sensorimotor Responding Following 20 Min of Active Exposure to Rearrangement; Binocular, Prisms Base Left, 10 Deg Lateral Displacement

Exposure Condition	Viewing Leg Movements (Eye-Foot Exposure)		Viewing Arm Movements (Eye-Hand Exposure)	
Test Subjects	Eye-Foot Coordination	Eye-Hand Coordination	Eye-Foot Coordination	Eye-Hand Coordination
1	1.0	7.4	0.6	5.6
2	1.5	10.0	−0.8	7.4
3	3.4	7.4	0.2	2.8
4	6.6	6.5	0.0	3.7
5	4.6	2.8	1.0	0.5
6	6.5	1.9	1.9	6.5
7	2.1	10.0	0.8	8.4
8	6.6	2.8	−0.2	2.8
Mean	4.0	6.1	0.3	4.7
Per Cent Adaptation	40	61	3	47
P (t-test)	<0.01	<0.01	N.S.	<0.01

Exposure Procedure

Four conditions of exposure to prism rearrangement were used in four experimental sessions, each separated by at least 24 h. The prisms were binocular base left 20-diopter wedges. Each session entailed two types of sensorimotor tests followed by exposure to rearrangement and then postexposure tests of the same coordinations. The exposure conditions and sensorimotor tests were as follows:

(1) Walking with prism vision. S walked for 50 min in a normally illuminated hallway while wearing prism goggles. He was instructed not to look at his feet, an act requiring substantial bending of the neck due to reduction of the visual field by the goggles. Sensorimotor tests: egocentric localization and eye-foot coordination.

(2) Prism viewing of leg movements. Seated at the exposure table, S moved his right leg from side to side for 50 min while viewing it through the prisms mounted on the slanted table top. Sensorimotor tests: egocentric localization and eye-foot coordination.

(3) Same as above (2) except that leg movements were viewed for only 20 min. Sensorimotor tests: eye-foot coordination and eye-hand coordination.

(4) Prism viewing of arm movements. Seated at the exposure table with the opaque surface covering view of his legs, S moved his right arm from side to side for 20 min while viewing it through prisms. Sensorimotor tests: eye-foot coordination and eye-hand coordination.

Order of experimental sessions as well as sequence of sensorimotor tests in pre- and postexposure measurements were permuted among the Ss. The design called for within-S comparison; thus each S served as his own control.

RESULTS

The results are shown in Tables 1 and 2. The measurements were made without prisms and thus represent aftereffects. The numerical values under "egocentric localization" are mean differences in degrees of visual angle between pre- and postexposure localization "errors" of the straight ahead; those under eye-foot and eye-hand coordination are the mean differences, in degrees of visual angle, between the centroids of the preexposure markings of the four targets and those of the postexposure.

Significant (t test for correlated means) changes in egocentric localization as well as in eye-foot coordination occur following 50 min of walking with prisms (Table 1). These are all in the expected (adaptive) direction. While the mean change in egocentric localization appears smaller than that observed in eye-foot coordination, the difference is not statistically reliable. Analogous changes occur following 50 min of viewing leg movements; however, the relative changes in eye-foot coordination in this case are significantly greater than those in egocentric localization (t test for correlated means). The changes in egocentric localization following both exposure conditions are statistically equivalent.

Twenty minutes of eye-foot exposure generates significant ($p < .05$, t test for correlated means) changes in eye-foot and eye-hand coordination (Table 2). The changes in the latter are significantly greater than those in the former. Viewing arm movements through prisms for the same period generates reliable changes only in eye-hand coordination.

DISCUSSION

Adaptive changes in egocentric localization and eye-foot coordination occur when a S walks with prisms, without viewing his legs (Table 1). The magnitude of adaptation in both sets of responses is equivalent. Changes in eye-hand coordination, also produced by walking with prisms, were earlier said to be similarly related. Thus, walking with prisms produces generalized alterations in sensory-guided responding. The "reafference" model (Held & Freedman, 1963) explains this in the following manner. Walking with prisms generates changes in target-oriented directions of the head; all responses entailing visual guidance, mediated through the new relationship between centrally controlled movements and spatial orientation of the head, are altered correspondingly. This alteration is in the same direction and of equal magnitude for all responses.

Viewing leg movements through prisms is also conducive to generalized adaptation as reported earlier by Hamilton (1964). Eye-hand coordination and egocentric localization change along with eye-foot coordination, although the arm is excluded from view and head movements reduced during exposure. This suggests that reafference from prism-viewed leg movements possesses the same generality in altering target-oriented directions of the head as reafference from walking with prisms. One can speculate that the highly consistent and stable relationship between movements of the leg and locomotor movements of the body as an integrated unit, during everyday life, underlie such a functional equivalence.

The data (Table 1) show that changes in egocentric localization, following 50 min of viewing leg movements, do not vary significantly from similar changes produced by 50 min of walking with prisms. The concurrent changes in eye-foot coordination, however, are significantly larger when produced by the former exposure condition. The greater magnitude of eye-foot coordination change produced by viewing leg movements through prisms allows an intriguing hypothesis. In addition to changing target-oriented head directions, reafference from leg movements recalibrates directed movements of limbs upon target-oriented directions of the head. The resultant change in eye-limb coordination should reflect the sum of both of these changes, yielding the larger magnitude of change in eye-foot coordination.

Twenty minutes of eye-hand exposure to rearrangement produces significant (t test for correlated means) adaptation in eye-hand coordination but has no reliable effect upon eye-foot coordination (Table 2). This is as expected since arm movements, being mostly dissociated from responses entailing the body or the legs, produce reafference relevant only to arm responses. The relatively large magnitude of adaptation is indicative of the plasticity of eye-hand coordinations.

Leg movements viewed through prisms for 20 min generate changes in both eye-hand and eye-foot coordination, thus again corroborating Hamilton's findings. It appears that information from leg movements are relevant for the recalibration of arm as well as leg responses, indicating that reafference from this source is useful for the recalibration of sensory-guided responses generally. The fact that larger changes in eye-hand coordination are generated with prism-viewed leg movements than with arm movements follows from the hypothesis discussed above. Leg movements produce reafference that alter limb responses as well as target-oriented directions of the head, thereby augmenting the shift effected by remapping of limb responses.

The data clearly indicate that leg movements viewed through prisms generate changes in sensorimotor responding that correspond, in their generality, to those produced by walking with prisms. More data are required to explore the hypothesized relationship of the magnitude of these changes in the various categories of sensorimotor behavior. The generality of adaptation produced by viewing leg movements has implications for interlimb transfer to be reported later.

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NOTES

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