Journal of Experimental Psychology
1966, Vol. 71, No. 5, 725–731

SPATIAL ADAPTATION AND AFTEREFFECT WITH OPTICALLY TRANSFORMED VISION: EFFECTS OF ACTIVE AND PASSIVE RESPONDING AND THE RELATIONSHIP BETWEEN TEST AND EXPOSURE RESPONSES

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Adaptation and aftereffect to prism-induced spatial transformation of vision has been investigated in 2 experiments and a control series. In Experiment I kinesthetic-muscular responses without vision preceded and followed similar responses with prismatically transformed vision during an exposure phase, and in Experiment II a passive and active swinging movement of the arm was introduced during exposure. In the 4 control experiments responses were made without transformed vision during exposure. Significant aftereffects occurred in Experiments I and II but in neither did they vary in magnitude as a function of either passive or active responses during exposure, relation of test to exposure responses, or to type of response made during the test phase. No significant effects occurred in the control experiments. The significantly smaller mean aftereffect for Experiment II suggested that aftereffects from spatially transformed vision are largely a function of the spatial relationships between test and exposure responses.

If the spatial characteristics of visual input are transformed by means of an optical system a change in the relationship between the visual and proprioceptive systems occurs. If, for example, the hand viewed through a wedge prism appears displaced left, and *S* is required to place his hand directly beneath its center, he will compensate and place it to the right of center. In brief, the proprioceptive information from the positioned limb adapts to the transformed visual information. Moreover, this adaptation, which develops rapidly (Hamilton, 1964), outlasts the period of transformation so that an aftereffect occurs following restoration of normal vision.

These effects which were first observed by Czermak (1855) and Helmholtz (1867) have recently been extensively investigated by Held and his associates (see Held & Freedman, 1963). Held has argued that natural active movement of either the whole body or of a limb is crucial for the occurrence of adaptation. When activity during the period of transformation is either restricted or induced by an external force (i.e., passive movement) no comparable adaptation takes place. In a series of experiments (Held & Gottlieb, 1958; Held & Hein, 1958; Held & Schlank, 1959) movement of the arm by an external force during spatially transformed vision failed to produce shifts in localizing responses whereas self-induced movement results in significant shifts.

Consideration of the effects of exposure to optically transformed vision suggests that certain relevant variables may have been overlooked. Among these are the nature of the responses made before and after the exposure

[1] The assistance of Robin Burns and Keith Keen in the collection of data and in statistical analysis is gratefully acknowledged.

period (test phase), those made during the exposure phase, and the relationship between these two sets of responses. Since the test-phase responses serve as an index of the adaptation affects occurring during exposure, it can be argued that they may vary in their adequacy to index the effect. The aim of the first experiment was to investigate the effects on adaptation and aftereffect of kinesthetic (passive) and kinesthetic-motor (active) responses individually and in combination during both the test and exposure phases. Because significant aftereffects of similar magnitude occurred under all conditions in the first experiment, the purpose of the second was to examine the effects of spatial dissimilarity between test- and exposure-phase responses.

Since there is some confusion over the meaning of the term "positive" adaptation (Day & Singer, 1964) a clarification of terms is necessary. Consider a situation in which *S* is required to place his nonvisible hand beneath a point marked on a horizontal opaque screen. The screen is now removed and *S* observes his hand through a prism whose refractive properties are such that the hand is judged 2 in. to the left of its true position. When instructed to place his hand directly beneath the center of the prism (which is coincident with the point on the screen), he will place it to the right of center. That is, he will compensate for the left deviation. Now when *S* has made a number of such responses the screen is replaced. When instructed to position his hand, again nonvisible, directly beneath the point he will continue to deviate to the right. The visual-proprioceptive relationship developed during the exposure period persists. This direction of difference between the pre- and posttest will be called a positive aftereffect. The period of visual-spatial transformation will be referred to throughout as the exposure period.

Experiment I

Without vision, judgments of the movement or position of a limb are mediated by the kinesthetic system whose receptors are located in the region of the joints. Such spatial judgments do not involve the sensory system of muscle (Day & Singer, 1964; Goldscheider, 1898; Rose & Mountcastle, 1959). The muscle stretch receptors, however, are involved in judgments of the force with which a limb is applied or moved. In a typical reaching response, therefore the afferent systems of both joints and muscles serve to control the extent, direction, and force of movement. Since the musculature is involved, this type of response is usually referred to as "active" whereas the positioning of a limb by an external force, in which judgments are mediated by kinesthetic receptors alone, is described as "passive." In the following experiment an active kinesthetic-muscular response (KM) and a passive kinesthetic response (K) were used to investigate adaptation to prismatically transformed vision under four conditions. Since a trial consisted of a pretest, an exposure period, and a posttest, the four possible conditions were KM-KM-KM, K-K-K, KM-K-KM, and K-KM-K.

Method

Apparatus.—The apparatus shown schematically in Fig. 1 consisted of a boxlike structure mounted above a movable platform 18 in. wide constructed on the principle of an endless belt with rollers at each end. The box, which was open on both sides, was 33 in. long, 21 in. wide, and 10 in. high. In the center of the top was mounted a color corrected wedge prism whose upper surface ($3\frac{3}{4} \times 2\frac{3}{4}$ in.) was flush with the top of the box. A headrest (not shown in Fig. 1)

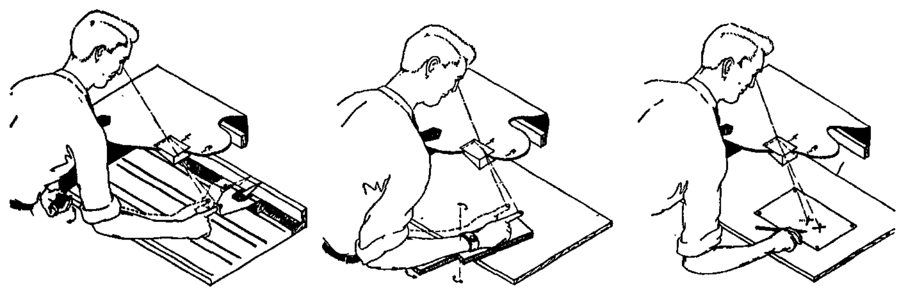

FIG. 1. Schematic representation of apparatus and type of response for the three experiments. (Left: K response showing true—full line—and apparent—dotted line—position of hand during exposure. Center: method of exposure responding for Exp. II. Right: KM responses showing true—full line—and apparent—dotted line—position of crosses. The L and R index marks are also shown.)

maintained *S*'s eyes in a constant position such that the apparent position of a point on the movable platform viewed through the prism was 2 in. to the left of its true location. A white Masonite cover could be placed over the prism in a fixed position. On the edge of this cover furthest from *S* were two index marks; one in line with the center of the prism (L) and the other 4 in. to the right of it (R). These marks were repeated beneath the cover on the upper surface of the box near the prism and in line with those on the cover. To increase the illumination in the box and to prevent reflection by the prism two 25-w. incandescent lamps were placed at the centers of each end. These lamps were not visible to *S* when viewing through the prism. For the K responses a hinged aluminum bracket was fixed to the movable platform (Fig. 1 left). This held *S*'s extended but relaxed index finger in a fixed position while it was moved by *S* with his right hand from side to side by means of the 3-in. diameter control on the right. A pointer which extended from the position of the fingertip moved across a shelf projecting from the rear of the box and on the same level as the platform. The finger bracket was hinged so that it could be folded back out of the visual field. For the KM responses there was a removable aluminum tray to hold firmly stacks of 13 × 8 in. paper sheets. These sheets could be removed one at a time from the tray which was placed in a fixed position on the platform.

Sheets of graph paper, each with two reference lines 4 in. apart, were used to record responses during pre- and posttests. For the KM tasks these sheets were fixed to the platform so that the reference lines were in exact vertical alignment with the index marks. For K responses the record sheet was similarly fixed to the shelf. In the KM task the responses during the exposure period were made by *S* himself on separate sheets in the tray, but for the passive K task the responses were recorded by *E* on the same record sheet as for the pre- and posttests.

Subjects.—There were four groups of eight boy and girl *S*s. All were in the fourth grade of a high school and between 16 and 17 yr.

Procedure.—The K responses for the pre- and posttests involved *S* moving his resting and nonvisible left index finger so that it was judged to be in vertical alignment with one of the two marks on the cover. The index finger was moved between these two positions by *S* with his right hand operating the rotary control (Fig. 1, left). There were 10 alternating responses for both pre- and posttest, 5 in line with L and 5 in line with R. The position of the finger indicated by the pointer after each response was marked by *E* on the graph paper pinned to the shelf. The KM responses during pre- and posttests merely consisted of *S* marking crosses in apparent vertical alignment with the two marks on the cover (Fig. 1, right). Five crosses were marked in vertical alignment with L and five in alignment with R. To prevent sequential effects the starting position of the hand was varied between 1.0 in., 0.5 in. to the right and left of the index marks and alignment with them. There was a different random order of these five positions for the L and R index marks for each *S*.

For the exposure period the cover was removed and *S* viewed his hand, now optically displaced to the left, through the prism. During the K exposure period S moved his visible but passive hand by means of the rotary control operated by his other hand. The passive hand was moved until it was judged to be alternatively in vertical alignment with the L and R marks. There were 14 responses made at regular intervals during a period of 3 min. The instruction to S was to view his hand throughout this 3-min. period. The judgments were recorded by E in the same manner as during the pre- and posttests. For the KM exposure, S responded at the same rate and for the same time by making crosses while viewing his hand. Each cross was marked on a sheet of paper in the tray, one cross to each sheet so that one response could not be determined by that preceding it.

There were four groups. Group KM-KM made KM responses (crosses) during pretest, exposure, and posttest, and Group K-K made K responses (passive finger positioning) during the three phases. Group KM-K made KM responses during pre- and posttests and K responses during exposure, and Group K-KM made K responses during the two test phases and KM responses during exposure.

Results

The distance of the K and KM responses from the two reference lines corresponding to the R and L index marks were measured to the nearest 0.1 in. The mean positions of the two groups of five pretest responses were found and the differences between these means and each of the five corresponding posttest responses calculated. Differences in an expected direction (i.e., posttest response to the right of the pretest mean) were scored as positive aftereffects, and those in the opposite direction as negative. Thus for each S there were 10 difference (aftereffect) scores, 5 for the L mark and 5 for the R mark. The mean aftereffects based on the 10 scores for eight Ss are shown for the four groups in Fig. 2A. The distance of the K and KM responses from the reference lines during the exposure period were also measured and the means based on 14 responses per S found for the four groups. These means are also shown in Fig. 2A.

A two-way analysis of variance of the aftereffect data has shown that no significant effects are attributable to either KM or K conditions during the 3-min. exposure period, or to response conditions (KM or K) during the pre- and posttests. The interaction between these two variables also failed to achieve significance. The variance estimate from the analysis of variance has been used to establish whether the total mean for the 32 Ss is different from zero. This mean proved to be significant, $t(31) = 7.45$, $p < .001$. Thus it follows from the analysis of variance and the t test that whereas a significant aftereffect occurred under the four conditions, there were no significant effects attributable to the variables (K and KM responses during tests and exposure) under examination or to their interaction. That is, neither active nor passive responding during exposure, the type of response, or the relationship between test and exposure activities affected the magnitude of adaptation to prism exposure. It can also be seen from Fig. 2A that response displacement (adaptation) during the

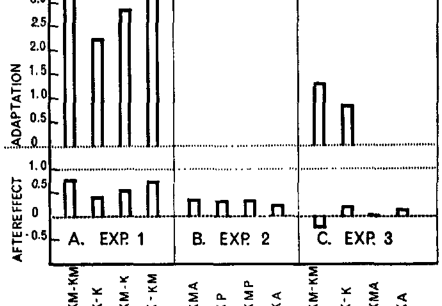

FIG. 2. Magnitude of adaptation and aftereffect for Exp. I(A), II(B), and the control conditions (C).

exposure phase was greater than the aftereffect and in excess of what would be predicted from the deviation (2 in.) of the prism. The reason for this effect will become clear below.

Experiment II

Since the effects of passive and active exposure responses in Exp. I were markedly different from those reported in other studies, the question arises as to the comparability of this and earlier experiments. In Exp. I the exposure and test responses were identical in *spatial* terms in that under all conditions *S* was required to locate two points 4 in. apart. In the experiments reported by Held and Gottlieb (1958) and Held and Hein (1958) the responses during exposure consisted of a lateral swinging motion of the arm while the test responses required *S* to locate the apparent position of a target. The differences in the degree of spatial relevance of test to exposure responses between Exp. I above and previously reported studies suggests a source of the inconsistency. It is reasonable to suggest that the differential effects of active and passive exposure responses are a function of the degree of spatial similarity or "relatedness" between test and exposure responses. The aim of the second experiment, therefore, was to examine the magnitude of prism-induced aftereffects as a function of active and passive exposure activity employing as before two types of test responses, KM and K.

Method

Apparatus.—The apparatus was the same as in Exp. I with the addition of a removable pivoted board (Fig. 1, center). The axis of the board was mounted so that it projected 2 in. above the surface of the movable platform and was located 10 in. from the right of the box relative to *S*. A strap screwed on to the upper surface held *S*'s hand firmly in position when the board was moved. The position of the board beneath the prism was such that *S*'s hand remained in view throughout an arc of 30°. The angle through which the board moved was governed by two adjustable stops. A metronome set at 60 beats/min controlled the rate of movement during exposure.

Subjects.—There were four groups each of 12 boy and girl *S*s drawn from the same grade (fourth) and age group (16–17 yr.) as for Exp. I.

Procedure.—Except for the exposure period the procedure was the same in all respects as in Exp. I including the type (K and KM) and number (10) of pre- and posttest responses, variation in starting position, and the method of recording and scoring responses.

For passive (P) movement during the 3-min. exposure period *S*'s hand was strapped on the board and, while *E* moved the board from side to side in time with the metronome, *S* viewed his hand through the prism. Throughout this period *S* was instructed to let his hand and arm remain quite limp and to relax them completely. During active (A) exposure *S*, with his arm in the same position, viewed his hand through the prism while moving it himself at the same rate and through the same arc. On completion of exposure the pivoted board was quickly removed and *S*'s hand placed in position for the first posttest response.

There were four groups. Group KMA made KM responses (crosses) during pre- and posttest and moved the hand actively during the 3-min. exposure period. Group KA made K responses (passive finger positioning) during the pre- and posttests and similarly moved the board during exposure. Groups KMP and KP made KM and K responses, respectively, during pre- and posttests but *E* moved the pivoted board during exposure while *S*'s hand and arm were relaxed.

Results

The mean differences between pre- and posttests each based on 10 differences per *S* are shown in Fig. 2B for the four groups. A two-way analysis of variance of the mean scores for each *S* has shown that there were no significant effects attributable to either passive or active conditions during the exposure period or to response conditions during the test phases. The interaction between these two variables also proved to be nonsignificant. The variance estimate derived from this analysis was used to establish whether the total mean for 48 *S*s was different from zero. This mean was found to be significant, $t(47) = 7.91$, $p < .001$. Thus whereas a significant aftereffect occurred under all four conditions there were no significant differences between the conditions.

Control Experiment

The measurement of an aftereffect from spatially transformed vision is usually carried out as in the present experiments by finding differences between responses made before and after a period of exposure to transformed visual input. It is conceivable, however, that these differences are independent of the experimental conditions. That is, the observed change could be a function of repeated trials reflecting practice or fatigue. In order to establish that the changes observed in Exp. I and II were due to prismatically transformed vision, four of the conditions used in the two experiments were repeated but with untransformed (i.e., normal) vision during the 3-in. exposure. It was considered unnecessary to repeat all eight conditions for the two experiments since if significant effects occur with normal vision a selection of the conditions would be enough to reveal them. For this reason Cond. KM-KM and K-K from Exp. I and KMA and KA from Exp. II were investigated with normal viewing during the exposure period.

The apparatus was the same as that used in the earlier experiments but the prism was removed from the top of the box so that *S* viewed his hand directly through the aperture. There were five *S*s per group all of whom were drawn from the same school grade and age group as before. The procedures, scoring, and all other details were identical to those of the earlier experiments.

The data for these controls are shown in Fig. 2C. Since the mean difference between pre- and posttest for all 20 *S*s is 0.04 in., and since 8 of the 20 *S*s gave negative effects, statistical treatment of these data was considered unnecessary. It is clear from Fig. 2C that the effects with normal vision during exposure are negligible.

For the two control conditions KM-KM and K-K for Exp. I, responses were measured for the exposure period and are shown in Fig. 2C. It is clear that these means are to the right of the L and R index marks. This observation explains why in Exp. I the prism-induced deviation from the true positions of L and R (Fig. 2A) exceeded those which would be expected from the 2-in. prism deviation. That is, there was constant error of localization in the frontal plane under normal viewing conditions.

Discussion

Although significant aftereffects from spatially transformed vision occurred in both experiments in neither did they vary significantly as a function of test responses (kinesthetic or kinesthetic-muscular), exposure responses (passive or active), or the relationship between these. A consideration of the joint data from the two experiments, however, is suggestive of the determinants of prism-induced aftereffects.

Since *S*s in Exp. I and II were drawn from the same population it is legitimate to compare the two means. The difference between these is significant, $t(78) = 3.54$, $p < .001$. These two experiments differed only in the responses made during the exposure period. In Exp. I responses under the four conditions and during the three phases of each condition were spatially near identical in that *S*s were required to make responses 4 in. apart. In Exp. II the responses (swinging movement) made during the exposure phase were spatially dissimilar to those during the pre- and posttest. It seems reasonable to suppose, therefore, that the significantly smaller aftereffects of Exp. II resulted from the spatially dissimilar responses between the test and exposure phases.

The data reported here are not consistent with those reported by Held and Hein (1958). From their experiment it was concluded that significant shifts in localization occur with self-produced motion during exposure, a conclusion which is supported by results from many experiments (Held & Freedman, 1963). The apparatus used by Held and Hein, however (see Held & Gottlieb, 1958), involved an oblique mirror from which the target was reflected to *S*'s eye. The outcome of this arrangement was that the target occupied an apparently higher (i.e., spatially dissimilar) position than that of *S*'s hand during exposure. It is conceivable that an interaction between the variables of passive movement and apparent position of target in the vertical dimension led to the smaller shifts for the passive condition. In any case, the graphic data reported by Held and Hein (1958) suggest that a slight shift did occur after passive movement.

In Exp. I the adaptation effect during exposure was measured in addition to the aftereffect. As shown in Fig. 2A the former effect was very large compared with the latter. Now, during a period of transformed vision it can be assumed that adaptation occurs and that this effect outlasts exposure. The present data suggest that if the postexposure responses are essentially similar in spatial terms to exposure responses, the persisting adaptation will be clearly revealed. If the postexposure responses are spatially dissimilar the effect will either not be revealed or revealed to a slight degree. In the simplest terms, if proprioceptive adaptation to spatially modified vision is to be measured, the responses used to index it need to be appropriate. Presumably adaptation is present after transformation of visual input irrespective of the nature of postexposure responses. Whether or not the effect is detected will be dependent on the spatial appropriateness of the responses. Failure to detect the effect may not necessarily indicate its absence so much as the unsuitability of the postexposure responses for its measurement.

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(Received January 18, 1965)