The constraints on learning new mappings between visual and proprioceptive spatial dimensions were assessed. Incomplete information was provided about a mapping by specifying only a few isolated visual–proprioceptive pairs of locations. The nature of the generalization occurring to untrained locations was then inspected to reveal the internal constraints. A new technique was developed to allow individual visual–proprioceptive pairs to be manipulated separately. In Experiment 1, training with only a single pair produced a rigid shift of one entire dimension with respect to the other. Training with two pairs caused linear interpolation to all untrained positions between the trained positions (Experiments 2 and 3). Finally, training with three new pairs also produced a linear change in behavior (Experiment 4), even though more adaptive solutions existed. The implications of these results for the learning process involved in acquiring new mappings are discussed.

A relatively neglected area of learning, with historical origins dating back to the British associationists, can be described as learning an association or mapping between two perceptual dimensions. Consider the 17th-century philosopher Berkeley's (1709/1910) claim that the visual experience of distance is acquired by the repeated joint experience of convergence of the eyes and reaching movements. Such experience, he claimed, caused each angle of convergence to invoke the "idea" of a particular-sized reaching movement, which in turn produced the experience of a particular distance. Although experience with reaching movements is no longer believed necessary to mediate the interpretation of visual distance cues, it is necessary in learning how to guide an arm to a target. How does each and every angle of convergence lead to a reaching movement of the correct size? That is, one problem encountered by perceptual systems is the association, not just between two stimuli, but between two entire dimensions of stimuli. Is a mapping simply a collection of individual associations, or are there specialized rules that operate when the entire lengths of two dimensions are to be connected?

This article explores the constraints on learning new mappings between two easily studied perceptual dimensions: the set of ordered angular positions in a one-dimensional array that are localized visually, and positions in the same array localized proprioceptively. If we let \( V \) and \( P \) represent values along the visual and proprioceptive spatial dimensions, then the normal adult mapping between these two dimensions can be described by the equation \( P = V \). For example, if a person sees an object 20° to the left, he or she can then point or reach, without visual guidance, 20° to the left. We can attempt to change this behavior by providing information that an object localized visually at one location is now to be found in a different location proprioceptively. Logically, there are an infinite number of new mappings, or lists, of such visual–proprioceptive pairs that can be presented. It should be possible to discover the rules that operate whenever new pairs are encountered, such that for every conceivable mapping between the two dimensions, one can predict the behavior that will result.

After an extensive review of studies on perceptual rearrangement, Welch (1978) concluded, "The most obvious fact is that human beings are capable of modifying their behavior in response to almost every imaginable stable rearrangement of vision" (p. 275). The review, however, was concerned mainly with one type of transformation for each of many different visual dimensions (such as the dimensions of orientation, depth, velocity, and horizontal position), rather than with many different types of transformations applied to a single visual dimension. On the other hand, Hay (1974) argued on theoretical grounds that there are limits on the class of transformations that can be learned. Empirically, however, only a small subset of mappings between the dimensions of visual and proprioceptive horizontal positions has been explored. The most commonly studied rearrangement is a simple, (nearly) uniform displacement of visual positions with respect to proprioceptive positions (roughly \( P = V + b \)) obtained by placing a wedge prism between a person and the world (see Howard, 1982; Welch, 1978, for reviews).

To uncover the constraints on learning new mappings, I investigated what would happen when only ambiguous, or incomplete, information was provided about a new mapping. An unambiguous, or complete, mapping is one in which a new proprioceptive position is designated for every single visual position. Though in practice it is difficult to provide such complete information, most experimental procedures do rearrange a continuous region of the visual dimension, which provides many visual–proprioceptive pairs. In the present...
study, a new proprioceptive partner was specified for each of only a few isolated visual locations, in order to observe what the system would fill in at untrained locations. Since this experimental situation does not specify any correct or "adaptive" behavior for untrained locations, the type of generalization that occurs reflects preferences and rules that the system itself brings to bear when learning new mappings. The strategy of providing incomplete information to reveal hidden rules has been used successfully in other areas; for example, in motion perception an apparent motion procedure is used to assess the path of motion interpolated in regions where no physical stimulus exists (Shepard, 1984).

In the present context, the smallest amount of information that can be provided experimentally involves training only one visual location with a new proprioceptive partner. The consequences of this training for untrained positions depends on how much structure already exists: The more internal structure, the more any one piece of external information can be used to generate behavior throughout the entire dimensions. I now describe three hypotheses about the amount of restrictive structure that might exist, corresponding to two extremes and one intermediate level of restriction, and note the predictions made by each hypothesis for single-pair training.

Minimum Constraint Hypothesis

At one extreme, there might be so few restrictions that all conceivable mappings could be learned equally well, including intuitively complex ones such as many-to-one and discontinuous mappings. Under such a minimum constraint hypothesis, there are an unlimited number of modifiable parameters; in other words, the only preexisting structure could be characterized as a list containing space for separate visual–proprioceptive pairs that are independent of each other. A mapping would simply be a collection of individual, independent connections between stimuli. Because a single visual–proprioceptive pair would be independent of all other pairs, the extreme form of this hypothesis anticipates that training at one visual location would induce a change only at that location. However, in practice it is likely that nearby visual locations would be mistaken for the training stimulus on some fraction of the trials, and furthermore, this probability of confusion would decrease at increasing separations. Consequently, the minimum constraint hypothesis can be taken as predicting the greatest change in pointing at the trained visual location, with decreasing impact for more distant locations.

This prediction is analogous to generalization gradients found in the more traditional learning paradigms of Pavlovian and instrumental conditioning, in which training with a single stimulus produces progressively less responding to stimuli increasingly removed from the training stimulus. There is a long history of comparing perceptual adaptation to traditional learning (e.g., Taub, 1968; Taylor, 1962); Epstein (1975), for example, argued that "the mechanism of recalibration is association by contiguity; the effect resembles sensory preconditioning" (p. 68). If a mapping between two entire dimensions of stimuli can be understood simply as a collection of independent "associations" between stimuli, then the single visual–proprioceptive pair is the correct unit of analysis of this system, and many of the principles that have been found to operate when single stimuli are associated in other areas might be relevant to learning involved in perceptual rearrangement.

Maximum Constraint Hypothesis

At the other extreme, the system may be so constrained that only the simplest mappings can be learned. An obvious candidate for such a simple mapping is one in which each proprioceptive position is offset from its corresponding visual position by exactly the same quantity, or $P = V + b$. Under this maximum constraint hypothesis, then, there is a rich preexisting structure such that only the value of a single parameter, the additive constant, can be changed through experience. Designating one visual–proprioceptive pair greatly limits the relation that can exist throughout the entire dimensions. Indeed, training at a single location would uniquely determine the constant and hence the remapping of the entire dimensions; a rigid shift in pointing at all visual locations is anticipated.

Intermediate Linear Constraint

Between these two extremes, there are, of course, many intermediate level of restrictions. A particularly notable one, which might be termed the intermediate linear constraint, corresponds to a modifiable slope as well as an intercept parameter ($P = aV + b$). This constraint would permit not only a rigid shift, but also a rescaling of the two dimensions. Held (1961) proposed that a "correlation storage" is used in adaptation to perceptual rearrangements; a simple version of a correlator would be one that looks for linear relations. Consider, first, that if the only rule brought to bear is "search for the best-fitting linear relation," then exposure to a single pair is insufficient to determine the two free parameters. Without further guiding rules (default values, for instance), not enough information is provided to drive the system, and learning at the trained location or any other visual location will not occur.

However, this alternative becomes particularly interesting if the perceptual system is viewed as attempting to accommodate its new experience with one particular visual–proprioceptive pair to its prior experience with other pairs. If normal coordination is itself a state of adaptation (Wallach & Floor, 1970), then pairs that satisfy the equation $P = V$ are already present before the experiment begins. These pairs result from everyday experience, in which objects are found proprioceptively in the same place they are localized visually. If the system attempts to fit a new linear relation to the totality of its experience, then the single experimental pair becomes sufficient to change the value of the two modifiable parameters; furthermore, how it changes depends upon the location of the new pair. A new proprioceptive partner designated for the exact central visual position will lead to a recalculated best-fit line with a different intercept but an unchanged slope (assuming left–right symmetry for the preexperimental pairs).
A new proprioceptive partner designated for a noncentral visual value, however, will lead to a new best-fit line with a change in slope as well as in intercept.

Figure 1 shows the different predictions of these three alternatives when a subject is exposed to a single, novel visual–proprioceptive pair that is not centrally located. The minimum constraint hypothesis predicts a highly localized change around the point of training, whereas the maximum constraint hypothesis predicts a rigid shift for all spatial positions. The intermediate linear constraint hypothesis (along with assumptions about preexisting experience) predicts a uniform rescaling characterized by a change in slope.

Surprisingly, the actual results of training with a single pair are not known. In many procedures a mapping is designated over a large range of the visual dimension; for example, a subject might be required to walk around (e.g., Redding, Clark, & Wallace, 1985), or to continuously watch his or her hand move from side to side (e.g., Hay, Langdon, & Pick, 1971) while looking through a prism. Even when the task is to point only to a single target (e.g., Redding & Wallace, 1978), subjects are exposed to many different pairs. In this procedure, a subject attempts to point to the target while looking through a prism, but does not see his or her hand until after the pointing motion is complete. Since the pointing response is visually unguided, initial errors are equal to the full magnitude of the image displacement. Each subsequent attempt brings the subject's hand closer to the target, until finally pointing is accurate. Consequently, every different position at which the hand is seen provides a distinct visual–proprioceptive pair; the finding that experience with a single visual–proprioceptive pair that is not centrally located. The minimum constraint hypothesis predicts a highly localized change around the point of training, whereas the maximum constraint hypothesis predicts a rigid shift for all spatial positions. The intermediate linear constraint hypothesis (along with assumptions about preexisting experience) predicts a uniform rescaling characterized by a change in slope.

Moreover, the most restrictive procedures, in which subjects view the hand in only one position, also provide multiple visual–proprioceptive pairs. In these studies, a subject either views the stationary hand (Held & Hein, 1958), views the stationary hand while his or her arm is being vibrated (Kravitz & Wallach, 1966), or views a single stroboscopically illuminated position of the hand while moving the arm back and forth (Moulden, 1971). While these studies find that the hand need not be viewed in motion to produce adaptation (provided that the salience of felt hand position is made high enough), they do not demonstrate that experience with a single visual–proprioceptive pair will also be sufficient. Because a hand has appreciable horizontal extent, both sides of the hand, as well as all places between, are visually displaced; hence information about multiple pairs is provided even for a single hand position. Of the few studies (Baily, 1972; Cohen, 1966; Harris, 1965; Hay et al., 1971) that have assessed generalization to visual locations not experienced in training, all have also designated a mapping over a continuous region of space.

In the present study, I used a new technique designed to control training at the level of discrete visual–proprioceptive pairs. Each subject wore a light-emitting diode (LED) on the finger; training on any one trial was restricted to experiencing a single visual position of the LED that occurred in close temporal proximity with the proprioceptive position of that LED. A variable prism adjusted by computer between trials enabled any proprioceptive position to be chosen for any visual position. Subjects were trained on one (Experiment 1), two (Experiments 2 and 3), or three (Experiment 4) new visual–proprioceptive pairs and the behavior at several locations was assessed.

**Experiment 1**

For three groups of subjects, a new proprioceptive partner was designated for a single visual position, located either centrally or to the left or right of center. A fourth group pointed to visual targets but was never permitted any visual information on the location of the hand. This group served as a control for any effects of looking, pointing, fatigue, or familiarity with equipment that the experimental groups had in addition to visual–proprioceptive training.

**Method**

**Subjects**

The subjects were 24 undergraduate and graduate students from the University of Pennsylvania paid for their participation. All subjects were right-handed and had normal or corrected-to-normal vision (contact lenses only).

**Apparatus**

The apparatus is shown in Figure 2. Each subject sat facing a semicircular array of red LEDs that were fixed in a wood panel covered with black nonreflecting felt. The LEDs were spaced 2.5° apart and were situated from 45° to the left of straight ahead (−) to 45° to the right of straight ahead (+), from the subject's point of view. Each LED was 6 mm in diameter and subtended .31° of visual angle at the viewing distance of 111.8 cm. A bite plate with dental wax was
Figure 2. Apparatus used by subjects for pointing to targets. (Apparatus is shown without finger LED, bite bar, or response button.)

used to keep each subject's head fixed in one position throughout the experiment.

A rod was used by each subject for pointing to the LEDs. It was located on a table surface 36 cm below the surface of the LED array; one end of the rod was fixed at the center of the table edge closest to the subject. The other end contained an upward stalk, on which the subject placed the index finger of his or her extended right hand and arm; the length of the rod was adjustable to accommodate arms of different lengths. The pointing motion was therefore side-to-side, with most of the movement from the shoulder joint. A potentiometer located directly underneath the pivot point was used to measure the angular position of the pointer. A black cuff containing a single red LED (diameter 4 mm, visual angle approximately .40°, depending on arm length) was attached to the pointing rod with a long wire. The cuff was wrapped around each subject's index finger such that the LED was directly above the finger tip. A response button held in the subject's left hand was used to indicate a completed pointing response.

An IBM personal computer (PC) was used to control onset and offset of all the LEDs and to receive input from the pointer and the response button. Pointer positions were converted from voltage to digital output using an analog-to-digital converter; the resolution of the pointer's angle was .5°.

In this experiment, a 20-diopter (11.3°) wedge prism mounted base left in the right eyepiece of goggles was used to produce the visual-proprioceptive offsets of 11.3°. The left eyepiece was blocked off, and each subject wore an eye patch over the left eye when the goggles were not being worn. (In all subsequent experiments a variable prism fixed to the upper surface was used; see the “Apparatus” section of Experiment 2.)

Procedure

Each subject was assigned randomly to one of the four groups with the restriction that the male–female ratio be kept roughly the same for all groups. The experiment consisted of three main parts: a preexposure test phase (pretest), an exposure phase (exposure), and a postexposure test phase (posttest). The test phases were identical for all groups and the exposure phase differed.

Pretest. The purpose of the pretest phase was to obtain a measure of how accurately subjects would point to visual targets without seeing their hands, before they received any training. A single, target LED was illuminated in an otherwise dark room. Each subject was instructed to point in such a way that the eye, the tip of the finger, and the target light were all felt to lie along the same line. When satisfied with the judgment, the subject pushed the response button, which caused the light to be extinguished, the pointing response to be recorded, and a new target light to be illuminated after 2.4 s. During the intertrial interval each subject was required to swing his or her arm back and forth at least once, to minimize correlation between errors. Following one practice trial of pointing at each of 3 target lights located at –5°, 0°, and 5°, any questions the subject had were answered and the test phase began. A total of 22 trials were presented in random order. Each trial consisted of two repetitions at each of the following locations: –25°, –20°, –15°, –10°, –5°, 0°, 5°, 10°, 15°, 20°, and 25°. Pilot work had found a drift in pointing to occur when visual feedback was withheld from pointing responses for extended periods of time. Consequently, testing (including practice and recorded trials) was kept to a minimum. Any subject who had a mean pointing bias of 5° or more in either direction was eliminated from the study. Five subjects were eliminated for failing to meet this criterion, and were replaced.

Exposure. The purpose of the exposure phase was to train subjects with a single new visual-proprioceptive pair. The eye patch was removed and the goggles placed on the subject's head. To limit exposure on each trial to a single pair, a new procedure was developed that combined and extended two existing procedures. As in the pretest phase, a single LED (the "target LED") was illuminated in an otherwise dark room, and subjects were required to point to the target LED. However, in this phase, whenever a subject's arm was lined up with the true position of the target LED, the LED worn on his or her finger (the "finger LED") was also illuminated. The subject's task was to get the finger LED lit and keep it lit for as much of the time as he or she could while the target LED remained illuminated. The target LED remained illuminated for a fixed 7.6 s on each trial, independent of a subject's performance. When a subject succeeded in illuminating the finger LED, he or she would localize the LED proprioceptively in one place, but because the subject was looking through a prism, he or she would localize this same LED visually in a different place. Thus the sight and feel of the finger LED occurring in close temporal proximity constituted the visual-proprioceptive pair. (The target LED remained illuminated during this time; its role in the learning process is not clear.)

This procedure uses the logic of the procedure of Moulden (1971) mentioned in the introduction, in which visual feedback is made contingent upon a particular arm position, rather than being provided continuously or following any pointing response. However, whereas in Moulden's procedure the entire room was stroboscopically illuminated, the type of feedback used in this experiment was more restrictive and was similar to one invented by Welch (1972), in which a subject watched nothing but his or her finger, coated with luminous paint, in an otherwise dark room. The substitution of an LED for a luminous finger made it easy to have the feedback contingent on arm position, and also further reduced the horizontal extent of the visual stimulus. The width of the LED, which subtended less than 4½° of visual angle, seemed small enough to be considered a single position. Also, a single LED worn on the finger presumably sufficed to convince a subject that he or she was, in fact, looking at his or her own finger, even when the LED appeared visually to be to one side of where the subject felt the finger was located. Welch (1972) found not only that feedback from a luminous finger is sufficient to produce adaptation, but also that substituting an experimenter's luminous finger and telling a subject it is his or her own (and to some extent, correctly informing the subject it is not his or her own) is also effective. It
appears difficult to destroy a subject's assumption that simultaneously registered visual and proprioceptive positions arise from the same distal object.

Each subject was warned that it would be difficult at first to illuminate the LED on his finger, because being in the dark is disorienting. The difficulty, of course, arose because the apparent visual position of the target LED viewed through the prism (of whose function the subject was not informed) was not the same as the position to which a subject had to point to line up his or her finger with the target's true location. Subjects were observed by the experimenter until they met the criterion of successfully illuminating the finger LED on 3 trials. During this time, general encouraging statements were made such as, "Try moving your hand back and forth slowly; that usually helps." No subjects were eliminated from the experiment for failing to meet this criterion. Pointing accuracy was recorded for each trial right before the target LED was extinguished. Because a pointing movement of approximately 1/4° on either side of the target would turn off the finger LED, subjects were also informed that once they were successful, it would take practice to keep the finger LED on steadily. Besides restricting the feedback, this narrow acceptance range also forced subjects to attend to the task, thus reducing the likelihood that they would engage in other cognitive tasks. Simultaneously performing general cognitive tasks has been found to interfere with, and reduce the magnitude of, adaptation (Redding et al., 1985).

The four groups differed on the location of space where they received feedback (i.e., illumination of the finger LED). One group received feedback when the arm was correctly aligned with a target LED appearing visually to be nearly 15° to the left (left group), another group when the target LED appeared nearly 15° to the right (right group), and a third group when the target LED appeared nearly straight ahead (central group). All groups, however, were presented with all three target LEDs during the training phase. For the two other targets, subjects did not receive feedback but were instructed to point in such a way that they felt their eye, the tip of their finger, and the target light to be lined up. Presenting all three targets to all groups ensured that any difference among the groups was due to the feedback itself. It also served to prevent specific motor response learning, which occurs when a single position is pointed to repeatedly (Redding & Wallace, 1978), and to minimize muscle potentiation effects that occur when noncentral muscle positions are maintained (see, e.g., Paap & Ebenholtz, 1976). A fourth group pointed to all three target lights, but did not receive feedback on any of them (no-feedback group), thus controlling for effects of looking, pointing, fatigue, and familiarity with equipment. To enable subjects (in the experimental groups) to distinguish between those trials when the finger LED could be illuminated and those when it could not, a beep generated by the IBM PC (located behind and to one side of the subject) accompanied the onset of the target LED for the feedback trials only. The exact visual–proprioceptive pair for the left group was (-13.7°, -11.3°); the pair for the central group was (1.3°, -11.3°); the pair for the right group was (16.3°, -11.3°).

Results

The mean changes in pointing as a function of target position for the four groups are shown in Figure 3. Training at a single position was sufficient to produce learning in the experimental groups. This can be seen by the substantial shift in pointing at the target position closest to the trained position for each group. Furthermore, all the changes were primarily rigid shifts across the tested locations. That is, the three curves are approximately parallel and flat, suggesting that within each group the change in pointing was the same size for trained and untrained target positions.

Visual inspection was supported by an analysis of variance (ANOVA) performed on pointer deviations (pointer positions − target positions), with phase (pretest and posttest), group (left, right, central, and no feedback), and target location (11 positions ranging from -25° through 25°) as variables. A significant main effect of phase, F(1, 20) = 104.6, p < .001, reflects the overall success of the one-pair training procedure. The group-by-phase interaction, F(3, 20) = 26.4, p < .001, and the group main effect, F(3, 20) = 5.5, p < .01, show a difference between the groups, due in part to an expected lack of adaptation in the control group. Differences in overall magnitude of learning among the experimental groups are analyzed below. There is no significant effect of target location (F<1) or target location-by-phase interaction (F<1), but a significant triple interaction between group, target location, and phase, F(30, 200) = 1.7, p < .05, suggests that adaptation did differ across targets.

Further analysis of the data for trends across target positions, however, found this variation to be small and unrelated to predictions. To analyze the trends across target positions, separate one-way ANOVAs on the changes in pointing (posttest − pretest) were performed on the data from each group. The target sum of squares was then partitioned into linear, quadratic, and cubic components, and each relationship was tested separately against the target-by-subject interaction before the remaining sum of squares was pooled into one higher-order component (e.g., Hays, 1973, pp. 687–694; also see Hay et al., 1971, who used this analysis). The maximum constraint hypothesis predicts no changes in any of the components for any group. The intermediate linear constraint hypothesis predicts a significant positive slope change for the left training group, a negative slope change of the same magnitude for the right training group, and no slope change for the central training group. The minimum constraint hypothesis predicts a significant second-order component. Analysis revealed a small positive change in slope (of .06) for the left group, F(1, 50) = 12.5, p < .001, but there was no equal and opposite
change for the right group ($M = +.01; F < 1$). There was also a small unexpected negative slope change (of $-0.07$) in the central group, $F(1, 50) = 12.4, p < .001$, and in the no-feedback group (of $-0.04$), $F(1, 50) = 5.9, p < .025$. With respect to the control group, both noncentral experimental groups showed a positive change in slope, which is not consistent with the prediction of the linear constraint hypothesis. Although an explanation for the slope changes occurring in the control group and the experimental groups is not readily apparent, these changes account for only a small part of the overall effect of training. There were no significant quadratic, cubic, or higher order components in any of the four groups, suggesting that there is no generalization decrement. ($F < 1$ in 8 of the 12 comparisons and $F < 1.8$ in the remaining 4, $p > .1$.)

The mean changes in intercept for the left, central, right and no feedback groups were, respectively, $-4.8^\circ$, $-9.2^\circ$, $-4.7^\circ$ and $1.4^\circ$. These values were significantly different from 0 in all three experimental groups but not in the control group. (The data are based on the average of the intercept values of best-fit lines calculated for each subject's data; two-tailed $t$ values are, respectively, $t(5) = 7.3, p < .001$; $t(5) = 9.9, p < .001$; $t(5) = 4.4, p < .005$; and $t(5) = 2.0, p > .1$.) The intercept changes, along with the small, unsystematic slope changes and the lack of any further significant trend, suggest that there was complete generalization from the trained location to all locations tested.

An unexpected finding was the difference in magnitude of the shift for the different experimental groups. Although the intercepts of the noncentral groups did not differ from each other, the intercept change for the central group was significantly greater, $t(16) = 4.0, p < .01$, than the average intercept change of the two noncentral groups. It is unlikely that the difference between the groups is simply due to the central groups receiving more visual-proprioceptive training trials than the other groups. All groups were highly successful at the task of illuminating the finger LED during the training phase: Mean deviations from accuracy (measured at the end

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Figure 3. Mean change in pointing as a function of target position for the four groups in Experiment 1. (The training pair for each group is indicated by the labeled, filled circle. L = left, C = central, R = right, Deg. = degrees.)
of each trial for the trained location and beginning with the first successful illumination were .06°, −.06°, and .38° for the left, central, and right groups, respectively. An ANOVA performed on the mean deviations for each subject found no difference between the groups \([F(2, 15) = 1.4, p > .1]\). Furthermore, all groups required approximately the same number of trials \((M = 4.3, 5.7, 5.0)\) before successfully illuminating the finger LED for the first time.

**Discussion**

Exposure to a single new visual–proprioceptive pair produced a global change throughout the entire mapping, rather than a focal change at the trained location. This change was a rigid shift, such that pointing shifted everywhere by an amount equal to the change at the trained location. Furthermore, the rigid shift occurred both when the trained visual location was located centrally and when it was located noncentrally. These results confirm the prediction made by the maximum constraint hypothesis. The finding that central training produced a greater shift than noncentral training does not contradict this hypothesis. There may be a greater certainty about the exact visual position of a target when it appears straight ahead than when it appears elsewhere. Consequently, any one visual–proprioceptive training trial containing a visual value of 0° might be more easily “registered,” and hence more effective, than one training trial with a different visual value.

However, there are several reasons why these data should not be taken to mean that the intercept is the only modifiable parameter. First, the rigid shift might indicate a preference rather than an absolute limitation. For example, according to a more complicated “stepwise constraint,” the perceptual system might first change the intercept, and then change other higher order parameters only as needed. Second, a rigid shift could still be consistent with the intermediate linear constraint hypothesis if the right and left visual locations used in training were not sufficiently peripheral compared to the values previously existing. The greater the distance between the position of the new visual value and that of the most extreme old values, the smaller the expected slope change for a new line that is calculated to accommodate all the information. It is plausible to believe that the endpoints of the preexperimental normal pairs extend well beyond the positions of the noncentral training values, which suggests that the expected slope changes may be too small to detect. Finally, the minimum constraint hypothesis can still be consistent with the data because a rigid shift across all horizontal positions could also be interpreted as the failure to learn anything about horizontal positions. If the newly learned proprioceptive response (e.g., “point 11° to the left”) became associated not with a horizontal visual location but with some other aspect of the training procedure, that response would not vary with visual location during the test. If, for instance, the proprioceptive response became associated with the particular vertical displacement, it would be appropriate to make that response to all of the test stimuli, as they share that vertical displacement. This would account for why no generalization decrement was observed when subjects were tested only along the dimension of horizontal positions. An outcome of this sort is not infrequent in studies of stimulus generalization in nonhuman animals (see Mackintosh, 1974).

**Experiment 2**

To investigate further the constraints responsible for a rigid shift following exposure to one pair, the second experiment assessed the behavior following exposure to two pairs. If both visual–proprioceptive pairs contain offsets in the same direction, all of the hypotheses under consideration make similar predictions, a rigid shift throughout the continuum. That same outcome is anticipated if the intercept is the only modifiable parameter, if the system is seeking a best-fit line, or if the pointing response becomes associated with some feature other than horizontal visual position. However, these hypotheses make quite different predictions under circumstances in which the proprioceptive partners are offset from the visual positions by equal amounts but in opposite directions. Those predictions are illustrated in Figure 4.

Under the maximum constraint hypothesis, in which a single intercept parameter is computed for both displacements in opposite directions (and they are given equal weight), the resulting value will average to zero; hence, no change is anticipated. However, an intermediate linear constraint that allows modification of slope as well as intercept anticipates a sloping line connecting the two pairs. Under the minimum constraint hypothesis, exposure to two opposite offsets may be viewed as an example of discrimination learning in which different pointing responses are associated with different horizontal visual locations. In that view, features of the stimulus presentations other than horizontal location are uncorrelated with the proprioceptive response and hence should not control responding during the test. By analogy to similar discrimination training paradigms in nonhuman animals, we would expect to see differential performance at the two training locations, with generalization around each location.

Finally, one should note the possibility of a more sophisticated version of the maximum constraint hypothesis (maximum 2). A system constrained to a rigid shift that is faced with opposite offsets in different portions of the visual space might adapt by effectively splitting that space and calculating a different intercept for each portion of the space. This predicts a rigid shift equal to one of the trained offsets for part of the space, and a rigid shift equal to the other trained offset for the remainder of the space.

Experiments in which a large continuous range of the visual field is uniformly magnified or minified (e.g., Hay et al., 1971) find very small changes in slope compared to the changes in intercept that are found when the visual field is displaced. From the experimenter's point of view, the current two-pair manipulation can be considered a degraded variant of this

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2 It is important to note that the issue of constraints is completely separate from the issue of underlying components (e.g., Harris, 1965). The rigid shift in pointing to visual targets might be due, for example, to a rigid shift within the proprioceptive subsystem, but the fact that training at one location produced any change in pointing to untrained locations requires further explanation along the lines of constraints.
global procedure, as the range of (two) proprioceptive positions is also expanded or contracted with respect to (two) visual positions. Because it is not known, however, whether the system will respond to two new pairs as if they reflected a magnification mapping, the applicability of existing results is not yet clear.

In this experiment, four groups of subjects were all trained with identical visual locations (+15° and -15°) and identical size proprioceptive offsets (10°). For two of these groups, the offsets for both visual positions were in the same direction, either both to the left, or both to the right. For the other two groups, the offsets for the two visual positions were in opposite directions. Subjects were tested on pointing to auditory targets as well as visual targets, for reasons discussed in the procedure section.

Method

Subjects

The subjects were 32 undergraduates from the University of Pennsylvania who were right-handed, had normal or corrected-to-normal vision, and were paid for their participation.

Apparatus and Procedure

The apparatus was the same as in Experiment 1, except that a variable prism under the control of the IBM PC was used instead of the wedge prism to create the visual–proprioceptive offsets. The displacement created by the variable prism ranged from -30 to +30 diopters. The variable prism was mounted in the right eyepiece of a rigid plastic frame fixed to the upper surface of the apparatus. A stepping motor (Airpax 5V, 3.5 W, 230 steps/s) attached to the variable prism from underneath enabled the setting of the prism to be driven by computer.

Any change in apparatus raises the problem that new variables might be introduced that affect behavior. In particular, whereas the wedge prism had to be physically removed from a subject's head in order to reinstate normal vision for testing, the variable prism could be changed back to the point of no distortion without a subject's awareness. If subjects became aware of a visual distortion during the exposure phase, and furthermore were unaware that the distortion had been removed, then any conscious strategy developed to compensate for the visual distortion during exposure might persist into testing (Welch, 1978). This seemed unlikely, since subjects in the first experiment were not even aware that their vision had ever been distorted. (This was discovered by informal questioning at the end of the experiment.) However, to test whether introduction of the variable prism created this new problem, a phase in which subjects pointed to auditory targets was added before and after training. Small loudspeakers were added to the LED panel every 5° from -45° to +45°, and the sounds used were white noise. If a change in pointing to visual targets was due to a false belief that a visual distortion was not removed, then no change in pointing to auditory targets would be observed. Consequently, a change in pointing to auditory targets would be evidence against this possibility of "visual conscious correction."

Subjects were assigned randomly to one of the four groups, with two restrictions: that the male–female ratio, and the pretraining biases, be kept roughly the same in all groups. Subjects were assigned to groups following the visual pretest phase.

Visual pretest. This phase was the same as pretest of Experiment 1, except the -25° target was eliminated because it could not be seen through the variable prism. Seven subjects were eliminated for failing to meet the criterion of less than a 5° bias and were replaced.

Auditory pretest. Each subject was instructed to point to the location of a sound in such a way that it felt like the eye, the tip of the finger, and the sound were all in line, and to push the button when satisfied with the judgement. To make sound localization easier, the sound on each trial was turned on and off once every 1.6 s until the subject pushed the button. There were three repetitions at each of the following six positions: -25°, -15°, -5°, 5°, 15°, 25°.

Exposure. Each of four groups of subjects was trained with two visual–proprioceptive pairs. For the two groups with same direction offsets for both pairs, the (V, DP) pairs were (-15°, 10°; 15°, 10°) (left displacement) and (-15°, -10°; 15°, -10°) (right displacement). For the two groups with opposite direction offsets, the V, DP pairs were (-15°, 10°; 15°, -10°) (magnification) and (-15°, -10°; 15°, 10°) (minification). In coordinates of absolute proprioceptive position, the (V, P) pairs for the left displacement, right displacement, magnification, and minification groups were (-15°, -5°; 15°, 25°; -15°, -25°; 15°, 5°; -15°, -5°; 15°, 25°).

The +/-10° offsets were produced with the variable prism, which was moved to the appropriate setting between trials (requiring 9 s). For instance, if the visual–proprioceptive pair on one trial of the magnification group was to be (-15°, -5°), then the prism was set to displace the image -10°; if the next trial was (+15°, +5°), then the prism was changed during the intertrial interval to +10°. On those trials where the appropriate prism setting was the same as the setting on the previous trial (approximately half of trials for the magnification and minification groups, and all trials for the left and right displacement groups), the prism was also moved a total of 20° (first 10° away and then 10° back) to ensure that subjects could not receive any cues about the next trial from whether or not the the prism moved. Subjects were first trained to a criterion of successful finger LED illumination on 3 trials for each of the two visual positions. During each trial the target LED remained illuminated for a fixed 8.2 s. After this practice, subjects received 40 trials at each visual location, for a total of 80 feedback trials. For each of these trials, the target remained illuminated for 6.6 s. The trials were divided into two equal blocks and randomized within each block. The intertrial interval was 2.9 s.

Visual posttest. This phase was identical to the visual pretest phase and, as in Experiment 1, the difference between visual posttest and
pretest serves as the measure of change in pointing to different visual locations produced by training at two visual locations.

**Auditory posttest.** This phase was identical to the auditory pretest phase. The difference between auditory posttest and pretest serves as a measure of change in pointing to auditory locations, produced by the training at two visual locations.

**Results and Discussion**

The mean changes in pointing to visual targets are presented in Figure 5. The graph suggests that in all four groups a linear change occurred at the untrained target positions between the two trained positions.

Deviations in pointing were entered into an ANOVA with phase, group, and target as variables. The incomplete exposure procedure again proved effective, as indicated by the significant difference in adaptation between groups [group-by-phase interaction: $F(3, 28) = 40.2, p < .001$, and group main effect: $F(3, 28) = 7.3, p < .001$]. The main effect of phase was not significant, $F(1, 28) = 1.8, p > .1$, because the change in the right displacement group (and magnification group) canceled the equal and opposite effect of the left displacement group (and minification group). Analysis revealed that behavior across the target positions differed among the groups [target-by-group-by-phase interaction: $F(27, 252) = 7.5, p < .001$, and target-by-group interaction: $F(27, 252) = 5.8, p < .001$]. (The target-by-phase interaction was not significant, $F<1$, because the target effects of the magnification and minification group were opposite and again canceled; there was a significant main effect of target, $F(9, 252) = 6.9, p < .001$, due to a pretraining tendency for subjects to begin with an expanded pointing range.)

To further analyze the behavior as a function of target position in each group, the trend analysis used in Experiment 1 was again performed. As expected by all the hypotheses, both of the groups with offsets in the same direction show a rigid shift. There was no significant change in slope, quadratic, cubic, or higher order parameters in either group ($F < 1.5, p > .1$, in all eight tests). Intercept shifts of $-9.2^*$ and $7.3^*$ in the right and left displacement groups were significant, $t(7) = 7.9, p < .001$ and, $t(7) = 9.2, p < .001$, respectively. The results of the two groups with opposite direction offsets confirm the prediction of the intermediate linear constraint hypothesis. There were highly significant and substantial slope changes of $-35$ for magnification, $F(1, 63) = 74.9, p < .001$, and $-29$ for minification, $F(1, 63) = 84.0, p < .001$. In the minification group, none of the other components were significant, and in the magnification group there was a small, marginally significant, $F(1, 63) = 3.3, p < .1$, cubic component; the latter finding may reflect a flattening in the regions outside of testing.

![Figure 5](image-url)
The data were noisier when subjects pointed to auditory targets than when they pointed to visual targets, but the overall pattern of change is the same. In the right and left displacement groups there were intercept changes, in the predicted directions, of $-9.6^\circ$ and $3.8^\circ$, $t(7) = 5.2$, $p < .01$, and $t(7) = 2.1$, $p < .1$, respectively. In the right displacement group, there was no change in slope, quadratic, cubic, or higher order parameters ($F<1.5$), but in the left displacement group, a slope change (of .08) approached significance, $F(1, 35) = 2.9$, $p < .1$; if this is a real effect, an explanation is not obvious. In the magnification and minification groups there were slope changes in the predicted directions of $-2.5^\circ$ and $14^\circ$ [$F(1, 35) = 11.3, p < .005$, and $F(1, 35) = 13.7, p < .001$, respectively]. No other component approached significance for either group. These data suggest that using the variable prism, which could be returned to the point of no distortion without a subject's awareness, did not introduce any new problems. If subjects were using a strategy for pointing during testing because they believed their vision was still distorted, then no change in auditory pointing would be expected. Note that the similar pattern of the auditory and visual data also suggests that the underlying component of pointing changes in this paradigm might be changes within the proprioceptive subsystem, suggesting that the constraints might apply to this level of the system.

The slope changes in pointing to visual and auditory targets support the intermediate linear constraint hypothesis. Although there are an infinite number of possible solutions consistent with the training pairs, the pattern of changes suggests that the system attempts a linear solution in which both the intercept and the slope are capable of modification.

Two alternative interpretations of the data, however, need to be considered. First, the gross features of the present results are potentially consistent with the more sophisticated version of the maximum constraint hypothesis (maximum 2), which permits space to be split into two parts and a separate intercept to be calculated for each part. In the absence of further constraining information, placing the break anywhere between the two training locations provides an equally adaptive solution. If different subjects arrive at different solutions, then a given intermediate testing point may lie to the left of the split for some subjects but to the right for the others. Thus, what appears in the average data to be a (linear) change in pointing as a function of visual target position, might be due to a (linear) change in the number of subjects who are pointing in each direction. Moreover, since the discontinuity would be located between the two training points for all subjects, this hypothesis anticipates that all subjects will respond in the same direction outside the training range. This could account for the apparent flattening in those regions.

If each mean slope change results from averaging two opposite-direction responses, a bimodal distribution of responding between the two training stimuli is anticipated. This, in turn, has consequences for the expected variances in performance. Variance should be greatest between the training points, where performance reflects bimodality, and least at the training points and beyond, where behavior reflects a homogeneous state. A technique recently developed by Sternberg, Knoll, and Turock (1986) allows exact variance predic-

tions for all mixture probabilities to be made based on actual variance at the pure states, probabilities of being in either pure state, and the difference between the means of the pure states. Following this technique, for each of the 5 interpolative visual target positions for the magnification and the minification groups, the predicted variance was calculated and compared to the actual variance. In 9 of the 10 comparisons, the actual variance was smaller than predicted; the mean ratio of actual to predicted variance was .446 ($SE = .097$). This value is significantly different, $t(9) = 5.7, p < .001$, from the ratio of 1, the value expected if the mixed model were correct. The modified maximum constraint hypothesis therefore does not seem a plausible account of these results.

Second, the observed slope changes might be due to broad generalization gradients surrounding each training value. Each slope change can be accounted for by two gradients that decline linearly to zero in $15^\circ$, or by two broader underlying gradients (linear or nonlinear) whose effects combine. While it would be difficult to reconcile such broad gradients with the minimum constraint hypothesis, the present experiment cannot rule out this alternative. According to the hypothesis, training at one visual location will, in theory, affect only that location, because all visual–proprioceptive pairs are independent of one another. A narrow generalization gradient was predicted because, in practice, nearby visual positions might be mistaken for the training position on some fraction of the trials. To account for the present data one would have to propose that a lot of confusion was present. For instance, in the magnification group, the $-5^\circ$ stimulus would have to be mistaken for the $-15^\circ$ training stimulus about 50% of the time, since the size of the response at $-5^\circ$ is about 50% of the size of the response at $-15^\circ$. Nonetheless, if the correct characterization of each slope change is two broad generalization gradients due to stimulus confusion, then the minimum constraint hypothesis can still be correct.

Moreover, if the apparent flattening at the $+/20^\circ$, and $+25^\circ$ targets is a real effect, then this behavior could reflect these broad generalization gradients. The range of targets tested outside of the training positions was not large enough in this experiment to determine the behavior in these critical regions. Consequently, behavior in the outside regions was the focus of the third experiment.

**Experiment 3**

To distinguish between the intermediate linear constraint hypothesis and the minimum constraint hypothesis, the behavior at those target positions located on the outside of the training positions was examined more closely in a magnification group. Whereas the former hypothesis predicts an extrapolation of the fitted line to the outside regions, the latter hypothesis makes the opposite prediction of a sloping generalization gradient that decreases to zero (see Figure 6).

Subjects were again exposed to two new visual–proprioceptive pairs with opposite direction offsets, except the visual positions were brought closer together to allow more positions located on the outside of the training positions to be tested. Furthermore, to ensure that any extrapolation would not be masked by an upper limit on the size of permissible pointing
Apparatus and Procedure

The apparatus and the procedure were identical to Experiment 2, except that there were two groups instead of four (magnification and vision; and were paid for their participation.

 Subjects

The subjects were 16 undergraduates from the University of Pennsylvania who were right-handed, had normal or corrected-to-normal vision, and were paid for their participation.

 Method

The apparatus and the procedure were identical to Experiment 2, except that there were two groups instead of four (magnification and left displacement), and the visual–proprioceptive training pairs were changed; the visual locations were +/-7.5° instead of +/-15° and the proprioceptive offsets were +/-5° instead of +/-10°. The (V, P) pairs for the magnification and the displacement groups then were, respectively, (-7.5°, -2.5°; 7.5°, 2.5°); (-7.5°, -2.5°; 7.5°, 12.5°), and in V, ΔP coordinates: (-7.5°, 5°; 7.5°, -5°) and (-7.5°, 5°; 7.5°, 5°). Six subjects were eliminated for failing to meet the pretest criterion and were replaced.

 Results and Discussion

The mean changes in pointing to visual targets are presented in Figure 7. Exposure to the smaller offset produces results comparable to the larger offset used in Experiment 2: In the left displacement group, there was again a significant intercept change, t(7) = 3.4, p < .025, with no change in any of the higher order components (trend analysis found F < 1.4 in the four comparisons). The intercept change was 2.9° out of a possible 5°, or 57% complete, and was not significantly different, t(14) = 1.6, p > .1, from the 73% change (7.3° out of 10°) found in the left displacement group of Experiment 2.

The result of the magnification group is surprising: while there is no evidence of a generalization decrement outside the training positions, there is also no extrapolation to the outside region along the same line fit to the inside region between the training positions. Trend analysis found a significant linear component, F(1, 63) = 142.3, p < .001, and a marginally significant cubic component, F(1, 63) = 3.4, p < .1. (For all other components, F < 1). The cubic component reflects the different behavior in the outside regions. Trend analysis done separately on the interpolative and each extrapolative region reveals a large significant slope change of -.44, F(1, 14) = 9.5, p < .01, for the positions between training points, but the smaller slope changes of -.15 and -.10 for the left and right regions, respectively, do not reach significance, F(1, 14) = 1.3, p > .1, and F(1, 21) = 1.6, p > .1. This suggests that if there is extrapolation along a sloping line, it is small in relation to variability.

The failure to detect a generalization decrement argues against the minimum constraint hypothesis, where the individual pair is the unit. It is unlikely that the data in Experiment 2 resulted from gradients declining to zero in 15°, because there is no evidence in this experiment of any decline in the 15° region outside the training stimuli. While the present experiment cannot rule out an eventual decline in the pointing change for targets further away, stimulus confusion would be an implausible explanation. Other theories of generalization gradients that need not preclude such broad gradients (e.g. Shepard, 1986, 1987) might eventually prove applicable to these data. However, as a gradient becomes broader, the influence of each piece of information on the rest of the dimension increases. Consequently, as a gradient becomes broader, learning connections between dimensions becomes closer to changing the parameter values of a function than to learning a collection of individual, independent pairs.

At present, the data best support a revised form of the intermediate linear constraint hypothesis: Slope and intercept parameters are modified, at least for the interpolative region between the two training pairs. It is not yet clear how to characterize behavior in extrapolative regions. Further evidence for this hypothesis comes from the comparison of the slopes in the interpolative regions of the magnification group in this experiment to the magnification group in Experiment 2. Although the values of the training pairs are different for the two groups, both slope values should be the same because, theoretically, the best-fit line through the two training pairs is the same for both groups (ΔP = .67V). This prediction was confirmed: The slope changes of -.44 and -.49 obtained in the interpolative regions from Experiments 3 and 2, respectively, were not significantly different, t(14) = 0.3, p > .1.

Figure 6. Predictions of the minimum and intermediate constraint hypotheses in the extrapolative regions for two new training pairs with offsets in opposite directions. (Deg. = degrees.)
CONCLUSIONS ON LEARNING NEW MAPPINGS

Experiment 4

The purpose of Experiment 4 was to distinguish between the intermediate linear constraint hypothesis and the alternative stepwise constraint hypothesis proposed in the discussion of Experiment 1. According to the former hypothesis, the best-fitting linear relation (characterized by both slope and intercept) is determined whenever new information is presented, whereas according to the latter hypothesis, the system first seeks only its most preferred relation (characterized by intercept) and checks the fit. If the fit is unsuccessful, the system then seeks its next most preferred relation (characterized by slope) and continues this process along some preference ordering (e.g., from lower order to higher order polynomials) until an adaptive solution is found. Does training with only two pairs with opposite direction offsets produce a slope change because only slope and intercept values are ever calculated, or because in this particular situation an adaptive solution could be found without going beyond the slope parameter?

To answer this question, subjects were exposed to three new visual–proprioceptive pairs. Two of the pairs were identical to the minification group of Experiment 2, but a third pair was included that did not fall along the same line. If constrained by a linear function, then only slope and intercept will be modified even though a more adaptive solution exists. This predicts that pointing will be described by the straight line that best fits the three noncollinear pairs (see Figure 8). Alternatively, according to the stepwise constraint, a slope change will be judged insufficient, and a nonlinear, higher-

Figure 7. Mean change in pointing as a function of target position for the two groups in Experiment 3. (The two training pairs for each group are indicated by the labeled, filled circles. Mag = magnification, L = left displacement, Deg. = degrees.)

Figure 8. Predictions of the intermediate and stepwise constraint hypotheses for training with three new visual–proprioceptive pairs that are not collinear. (Deg. = degrees.)
order parameter will be modified. This predicts that the change in pointing will be described by a quadratic function that passes through all three pairs.

Method

Subjects

The subjects were 8 students (ages 15 to 20) enrolled in summer courses at the University of Pennsylvania who were right-handed, had normal or corrected-to-normal vision, and were paid for their participation.

Apparatus and Procedure

The apparatus and the procedure were identical to the minification group of Experiment 2, except that 40 exposure trials were added at a third visual-propioreceptive pair located at (0°, 10°). Half of the trials were intermixed into the first exposure block, and half of the trials into the second. Four subjects were rejected for failing to meet the pretest criterion and were replaced.

Results and Discussion

Figure 9 shows the primary result. The data suggest that a linear change occurred in pointing to visual targets between the training positions. Trend analysis found only a significant first order, \( F(1, 63) = 43.1, p < .001 \), and third order, \( F(1, 63) = 5.8, p < .025 \), component; there was no evidence of a change in the second-order term, \( F(1, 63) = 1.7, p > .1 \), or terms beyond the third \( F < 1 \). The change in the cubic component reflects an apparent leveling off in the regions outside of training, as was found in prior experiments. This interpretation of the cubic component was confirmed by the results of trend analysis repeated on just the interpolative region, where only the slope component proved significant, \( F(1, 63) = 30, p < .001 \) (\( F < 1 \) for all other comparisons).

The results support the intermediate linear constraint hypothesis, and argue against the stepwise constraint hypothesis. The data suggest that only slope and intercept parameters were modified between the training positions, despite the fact that a more adaptive solution exists. The inappropriateness can be seen most strikingly at the 0° target, where the change in pointing was less than that obtained for the +15° target, despite the fact that they were both trained with identical offsets (of +10°). The smaller pointing change at 0° is a consequence of the best-fit line under the circumstances and reflects the failure to arrive at a nonlinear solution. It is unlikely that subjects simply received less experience with the (0°, 10°) pair during training. First, analysis of the exposure data finds subjects equally successful at illuminating the finger LED, at least at the end of exposure trials, when the data were collected. Secondly, the results of Experiment 1, in which

![Figure 9](image-url)
training occurs at only one pair, suggest that the central pair is the most effective at producing a change in pointing.

It is useful to compare these results to the minimification group of Experiment 2, where training was provided at the same two noncentral pairs but without the central pair. The theoretical best-fit lines for Experiments 2 and 4 are, respectively:

$$\Delta P = .67V + 0$$
$$\Delta P = .67V + 3.33$$

We would expect from the intermediate linear constraint hypothesis that addition of the central pair would produce the same slope value, and would increase the intercept value, from those obtained in Experiment 2 (assuming a least squares criterion). This prediction was confirmed: the slope changes of .37 and .31 found in Experiments 4 and 2, respectively, were not significantly different, t(14) = 0.4, p > .1, and the intercept change of 1.7" in Experiment 4 was significantly more positive, t(14) = 2.3, p < .05, than the −1.6" change in Experiment 2. These values are based on best-fit lines in the interpolative regions.

Note that the linear change in this experiment also provides further evidence against the explanation that the slope change in Experiment 2 was due to the average of step functions, where each subject split the space in a different place between the −15° and +15° training positions. In this experiment, subjects could have reached a more adaptive solution had they split the space anywhere between −15° and 0° and fit a separate intercept for each part. Since a step function is not fit in this situation even though it is more adaptive than a slope change, it is unlikely that the step function would be preferred to a slope change in the situation of Experiment 2 or Experiment 3, in which both solutions are equally adaptive.

General Discussion

In summary, training with one visual–proprioceptive pair produces a rigid shift in pointing for all visual locations; training with two visual–proprioceptive pairs produces changes in pointing that lie along a line between the two pairs; and training with three visual–proprioceptive pairs that are not collinear also produces linear changes in pointing.

In my view, these results have two important implications for the learning process involved in acquiring new mappings between the visual and proprioceptive dimensions of horizontal positions. First, the process can be characterized as looking for a relation between an entire dimension of stimuli and an entire dimension of responses, rather than associating each individual stimulus with an individual response. Second, there is a linear constraint on this process, such that what is changed through experience is the value of a slope and of an intercept parameter. Each of these claims will be examined more closely.

The finding that training on individual pairs does not cause narrow generalization gradients surrounding each training value suggests that learning new mappings does not consist simply of a collection of separate connections between visual and proprioceptive stimuli. The individual visual–proprioceptive pair is not the unit of this learning process. The individual pair cannot be isolated and manipulated separately, or at least there is a strong preference not to so isolate it. Rather, what is acquired is a relationship or rule between entire dimensions of stimuli, such that behavior at both trained and untrained locations can be described by the calculated parameter values of a function (cf. Hay, 1974). One consequence of this finding is that what is learned after pairing a large number of stimuli with a large number of responses cannot be predicted simply by combining the behavior observed when each pair is trained in isolation. For instance, the slope change observed following training with two pairs with offsets of the same size but in opposite directions could not be calculated based on the sum of two intercept changes of the same size and in opposite directions—the outcome expected if each pair was trained by itself.

What does this suggest about the role of other learning processes, such as Pavlovian conditioning, where a bond between single stimuli is the implied unit? I would argue that it is still relevant; the present experiments also demonstrate that training with an individual pair is sufficient to change behavior. One may say that the individual visual–proprioceptive pair is the unit of input. Consequently, the principles governing when the two stimuli of any one pair of stimuli will be registered as "going together" are crucial for understanding the adaptation-learning process, and research in Pavlovian conditioning might have uncovered general principles on this issue. For instance, contiguity may be a general principle whereby entities that are close to one another are viewed as going together. Contiguity appears to be involved in forming Pavlovian associations among events, grouping spatially distributed entities (see Rescorla, 1985, for a comparison of principles common to associative learning and Gestalt grouping phenomena), and learning new mappings between dimensions. In addition to the contribution of general principles, associative experiments using more than one value from a stimulus dimension might be particularly relevant. The outcome of such experiments often cannot be predicted based on the result of reinforcing each stimulus in isolation (see Mackintosh, 1974). For example, when two stimuli that differed in the dimension of wavelength were both identically reinforced, responding was greater for those untrained wavelengths between the training stimuli than was predicted based on observed generalization gradients when each stimulus was reinforced separately (Blough, 1969). In other words, it is not clear that the single stimulus association is always the unit in traditional learning either. The present discrete-pair training procedure, rather than the usual rearrangement of a continuum, seems a more analogous paradigm in which to continue investigating the parallels between these two areas of learning.

The second important finding is that the system preferentially modifies intercept or slope when other equally adaptive solutions exist, and even when more adaptive solutions exist. It is important to note two clarifications of this "linear constraint." First, it does not imply that only linear mappings between the visual and proprioceptive horizontal dimensions can be learned. Although subjects fit a line through three nonlinear points, subjects may change other parameters if the number of points presented along the nonlinear function are
increased. In other words, a certain amount of error in a fitted function might be tolerated before less preferred relationships are sought. (Note that the amount of error tolerated might itself be fixed or changeable with experience.) The present experiments demonstrate a strong preference for modifying slope and intercept parameters, revealed through the technique of presenting highly unconstrained, or incomplete, information. By presenting more constrained, or more complete, information on the nature of a new mapping and determining how behavior deviates from the imposed distortion, the limits of adaptability can be determined (Hay et al., 1971). Whereas prior research on new mappings was largely dependent on the distortions produced by lenses, prisms, and other optical devices, the technique developed for the present study, whereby each proprioceptive partner can be specified separately for each visual position, enables the question of limiting constraints, as well as preferences, to be easily investigated.

Second, the linear constraint is only a partial characterization of the rules that operate when even only a few new visual–proprioceptive pairs are encountered. When the system was presented with pairs having offsets in opposite directions, extrapolation to the regions outside the training positions did not occur; rather, the change in pointing appeared to level off. This suggests that some other rule(s) may be used to generate behavior in the outside regions. Note that in the present study, extrapolation would have required producing a larger response (i.e., a larger offset between visual position and pointed position) than ever before experienced and would have required producing this response in a noncentral region of the visual dimension. Intuitively, both of these requirements seem difficult. A situation where extrapolation would instead produce a smaller response, for example, might produce different results. The rules that characterize behavior in the extrapolative regions are currently under investigation.

The present finding of a linear constraint raises several questions. One question is why slope is easily modified in this study, but appeared difficult to modify in previous experiments in the literature, in which a continuous region of the visual image was magnified or minified. For example, Hay et al. (1971) exposed subjects concurrently to a 24° lateral displacement and a two-factor magnification. This was accomplished by having each subject view his or her hand moving continuously back and forth in an illuminated room through a 40-diopter wedge prism. (A prism of this size produces appreciable magnification as well as displacement.) Whereas the pretest to posttest shift in pointing to visual targets revealed approximately 50% adaptation for the displacement component, no adaptation was found for the magnification component. In the second experiment, in which a convex lens was used so that the magnification distortion was "isolated and enhanced," a 5% change in slope was found. This amounted to a maximum change of 4°, compared to a shift of 12.5° found to displacement at the same target location. One account of this finding derives from the fact that when a subject's entire hand is visible during exposure, a magnification rearrangement magnifies not only the range of visual positions of the hand with respect to the range of proprioceptive positions of the hand, but also the appearance of the hand itself; with a displacement rearrangement, however, the range of visual positions is altered, but the appearance of the hand is not. Held (1970) argues that there are two distinct modes for processing spatially extended information: a "locus specific" system wherein the angular position of each point with respect to the observer is retained, and the "figural identification" system, wherein relational information among contours is processed. (A similar distinction is made by Rock, 1966, p. 180, who uses the terms "subject-relative aspect" and "object-relative aspect." ) Held further argues that if the locus specific system is easily changed and the system for form is not, then the two systems might contradict each other during exposure to some rearrangements and reduce the overall amount of adaptation observed to those rearrangements. In the experiment of Hay et al., adaptation to magnification may have been less than adaptation to displacement because the exposure to the magnification rearrangement introduced a form distortion, whereas the displacement rearrangement did not. In the present paradigm, wherein an LED instead of a hand is viewed in an otherwise dark room, there is not any spatially extended information available at any one time during exposure. This may force only the system that processes the angular position of each point with respect to the observer to be used for both rearrangements. It remains to be determined whether removal of spatially extended information is responsible for the different results, or whether there is some reason that slope might be more easily modified when magnification is specified with only two or three visual–proprioceptive pairs. Note that, to the extent that the two systems play different roles in adaptation, the present paradigm is also a useful one for isolating one system (also see Redding, 1975, who compared tilt and displacement in the absence of extended contours).

Two further questions concern a more detailed analysis of the constraint and the level at which the constraint occurs. First, further analysis of the linear constraint might reveal that slope and intercept changes are equally preferred, or alternatively, that a slope change is less preferred than an intercept change and that its value is calculated only if an intercept fit is judged unsuccessful. The finding that training with a single pair produces only an intercept shift (Experiment 1) is consistent with both of these hypotheses. The intercept shift can result from a calculation of the best-fit line (both slope and intercept) to the new pair combined with the "normal" preexperimental pairs already present or, if intercept is preferred over slope, from a calculation of only the best-fit intercept to the training pair. (These calculations can be made with or without considering old preexperimental pairs.) Wallach and Floor's (1970) procedure of training the normal state in the experimental apparatus in order to control which normal pairs will have an influence, may be helpful for distinguishing between these two alternative accounts of the linear constraint.

Second, it is useful to know the component(s) underlying the changes in pointing to visual targets, in order to determine the level at which the constraints apply. The same constraints do not necessarily exist at all levels of the system. For instance, the nonlinearity of the mapping in Experiment 4 may have been easily detected at the highest level, where the co-occur-
ference of visual and proprioceptive information is registered, but masked because the linear constraint is imposed at a lower level, such as within the proprioceptive subsystem (see Howard, 1982, for a model of the eye-hand coordination system). The change in pointing to auditory targets (Experiment 2) suggests that at least part of the change in pointing to visual targets is due to a change within the proprioceptive subsystem. Testing subjects with a variety of tasks, in addition to having subjects point to visual and auditory targets, is needed to determine more completely the underlying component(s) of the changes in the present paradigm (see Harris, 1965), and therefore to determine the level(s) at which the linear constraint applies.

A final question is, Why should there be a linear constraint at all? It is possible that the constraint is well matched to the particular problems that this adaptive system was designed to handle. For example, the errors in visual–proprioceptive spatial coordination resulting from naturally occurring drift between the two systems, or from growth of body parts, might also be characterized by a linear function. At the other extreme, the linear constraint might reflect a general solution to the general problem of associating entire dimensions of stimuli, independent of the content of those dimensions. It has been argued, regarding both perception (Shepard, 1984) and learning (Rozin & Schull, 1988), that constraints are often internalizations of general states of the world, rather than reflections of the varied details of individual problems. Linear functions characterize the relation between many dimensions in the world (Anderson, 1983); for example, distance is a linear function of time, with velocity held constant. Furthermore, when relationships are not linear, they often are linear over some central range (Carroll, 1963). Perhaps the failure to extrapolate observed in the present study reflects this knowledge, and is due to the general, cautious strategy of not assuming a linear relation in a noncentral region from which no information is obtained. The generality of the present “dimensional learning” process and its constraints is an area open for future exploration.

References


Rayner Appointed Editor of *JEP: Learning, Memory, and Cognition, 1990–1995*

The Publications and Communications Board of the American Psychological Association announces the appointment of Keith Rayner, University of Massachusetts, as editor of the *Journal of Experimental Psychology: Learning, Memory, and Cognition* for a 6-year term beginning in 1990. As of January 1, 1989, manuscripts should be directed to

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