"Adaptation" to Displacement Prisms Is Sensorimotor Learning

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Abstract

Observers reaching to a target seen through wedge shaped displacement prisms initially reach in the direction of displacement, correcting their reaches over a series of about 12 trials. With subsequent removal of the prisms, observers initially reach to the opposite side of the target, correcting over about 6 trials. This phenomenon has been called "adaptation" because of its similarity to the adaptation of sensory thresholds to prevailing energy levels. We show, however, that this perturbation to visually guided reaching only mimics sensory adaptation initially. Subsequent changes show that this is sensorimotor learning. Error in pointing to targets is the commonly used measure. We measured times for rapid reaches to place a stylus in a target. Participants wearing a prism worked to achieve criterion times previously established with normal, unperturbed vision. Blocks of trials with and without a prism were alternated. Both the number of trials to criterion and the mean times per block of trials decreased over successive blocks in a session, as well as over successive days. By the third day, participants were able to respond rapidly to perturbations. This reflects the acquisition of a new skill that must be similar to that acquired by users of corrective lens.

Introduction

Wedge shaped prisms bend the light projected to the eye so that rays enter the eye at an angle displaced from their original angular location about the point of observation. The direction of displacement is towards the apex of the wedge. The amount of displacement depends on the size of the wedge. Observers reaching towards a target seen through displacement prisms reach, on their first attempt, in the direction of displacement. Over a series of about 12 trials, observers correct their reaches so that eventually they reach directly towards the actual location of the target. With subsequent removal of the prisms, observers initially reach to the opposite side of the target, becoming correct over about 6 trials. This phenomenon has been called "adaptation" because of its similarity to the adaptation of sensory thresholds in response to changing ambient energy levels.

Adaptation of sensory thresholds exhibits time courses invariably described as negatively accelerated exponential curves with an asymmetry in the rate of adaptation depending on the direction of adjustment. For instance, adaptation of visual thresholds to darkness takes 20-30 min while adaptation to bright conditions[1] takes only 2-3 min. Likewise, the curves for gustatory adaptation, adaptation to cutaneous pressure, and adaptation to cutaneous pain exhibit asymmetry depending on direction (Schiff, 1980; Uttal, 1973). Characteristic of sensory adaptation functions is the relative constancy or stability of the relaxation times. Repeated adaptation of visual thresholds to alternating dark or bright conditions does not alter the respective times for adjustment. The magnitudes of these relaxation times reflect the character of the underlying neurophysiological events. The stability of these times reflects the relative simplicity of the underlying dynamics. Only two time scales are involved. A relatively

[1] This is often called "recovery" in recognition of the asymmetry.

fast time scale associated with detection as a threshold is exceeded and a slower time scale corresponding to the adjustment of the threshold level with adaptation.

The effect of displacement prisms is to perturb the perceptuomotor system used, for instance, in reaching. Referring to the response to this perturbation as "adaptation" is to imply that the underlying dynamic is similar to simple dynamic of sensory adaptation. Indeed, the analogy has been made explicitly with the suggestion that a single (correlational) transformation from sensory to motor variables plays the role of the threshold (Dolezal, 1982; Hein & Held, 1962; Held, 1961; 1965; 1968; 1980). The two time scales would be a relatively fast time scale associated with a process of sensorimotor transformation and a slower time scale corresponding to the time for adaptation to the effect of the prism or its removal.

While this holds out the promise of a relatively simple account, we suggest that the commonly successful use of lenses to correct visual dysfunction means that this approach is overly optimistic. The simple account cannot be correct. If it were, the use of corrective lenses would be much less effective and more problematic than it is. Users typically experience difficulties in adjusting to corrective lenses in the first couple of days. Thereafter, however, adjustment to the lenses is almost immediate as is the adjustment to their removal.

The implication is that the time required for adjustment to perturbation by displacement prisms is not constant, but decreases over repeated application of the perturbation. Thus, multiple time scales are involved, certainly more than two. Focusing on paradigmatic reaching with prisms, and starting with relatively fast time scales, there is the time for a single reach. This is on the order of a second. There is the time for adjustment to the prism or its removal. This is on the order of a few minutes. There is the time for change in the period of adjustment. This may be on the order of an hour or two or perhaps, a day or two.

Assuming that his latter change exists as our observations on corrective lenses suggests it must, it would constitute evidence for learning or sensorimotor skill acquisition. Is the adjustment to displacement prisms part of a process of skill acquisition? If so, then we might expect to see improvements in the ability to respond over the course of repeated perturbation on a single day with some retention of skill on a subsequent day and with continued improvements over days leading to an expert's level of skill. How skilled might an expert be? Might he or she be capable of immediate adjustment to prisms of various strengths? This is unlikely given that some period of adjustment is required even for a life long user of corrective lenses when a new prescription is obtained.

We investigated these questions by measuring the time course of rapid reaches to a target performed over alternating application of a displacement prism and its removal, allowing normal vision. We also began to investigate the nature of the potential skill by applying a stronger prism after successive adjustments to a weaker one. Subsequently, we will discuss the new questions that arise with the reconceptualization of this long standing problem in perception/action research.

Methods

Apparatus. All reaches were measured using a two-camera WATSMART system sampling infrared emitting diodes (IREDS) at 100 Hz. IREDS were placed on the dorsal side of the metacarpal–phalangeal joint of the right thumb, on the thumbnail, and around the right eye. The collection period was controlled by an external trigger housed in a launchpad and target. Data collection routines were initiated when a stylus was removed from the launchpad and terminated when the stylus was inserted into a target. Placement of the stylus in the launchpad broke an infrared beam, which set the clock at zero. Removal of the stylus from the launchpad triggered the internal timing mechanism with a maximum delay of 5 ms. Placement of the stylus into the target split a beam which terminated the clock. Movement times were displayed on a CRT at the end of each trial and recorded by the experimenter.

Three pairs of swimming goggles were instrumented to allow measurement of the head and eye position. In all cases, the left eye piece was blackened. The right eye piece was covered with a 9 cm by 4 cm piece of plexiglass which supported three IREDS, placed above, below, and to the right of the eye. Displacement prisms were mounted over the right eye of two of the sets of goggles. Visual displacement was 10° and 15°

to the right, respectively.

Participants. Eight adults, 5 male and 3 female, aged 18–28 years, participated in the experiment. All had good, uncorrected vision and had never worn corrective lens. All were free of motor disabilities. Participants were paid at $5.00/hr.

Procedure. Three experimental sessions were performed on consecutive days at approximately the same time each day. During testing, the participant was seated comfortably. Head movement was unrestricted. The participant's task was to remove a stylus from a launchpad and to place the stylus as rapidly as possible in a target hole by reaching with the right hand. The launchpad was located next to the participant's hip and the target was placed just above the participant's right knee. The target was positioned at a distance reachable by fully extending the arm without moving the shoulder or trunk. The angle of the target was determined by having the subject sight directly down the target hole. The task was performed under four visual conditions: binocular, monocular, monocular with a restricted field of view (clear goggles), and monocular with restricted field of view and displaced vision (prism goggles). The displacement was 10°.

The participant was instructed to move to the target as rapidly and accurately as possible, so as not to collide with the target face at a high speed. The participant was told not to use any targeting strategies other than aiming straight for the target itself. The participant's eyes remained closed except immediately before and during the reach.

The first 2 blocks consisted of 10 trials in each of the binocular and monocular conditions. The remainder of the experiment consisted of alternating blocks of clear goggle and prism trials. The initial clear goggle block consisted of 10 trials which were used to obtain the participant's criterion value. The participant was not aware that a criterion time was being established for use throughout the remainder of the experiment. The criterion value was determined by taking the mean of the participant's movement times for this block (minus the fastest and slowest trials) and adding one standard deviation.

Thereafter, the number of trials for each block varied, depending on the number of trials required for the participant to reach the criterion value during three consecutive trials. Participants were informed that they were trying to achieve reaches at or below criterion times. Alternating blocks of viewing conditions continued until the participant reached the criterion within a maximum of four trials for the prism condition. At this point, an additional round of clear goggles and prism blocks was performed ending with a final block of the clear goggles trials. This was followed by a prism block with a 15° displacement prism.

Results and Discussion

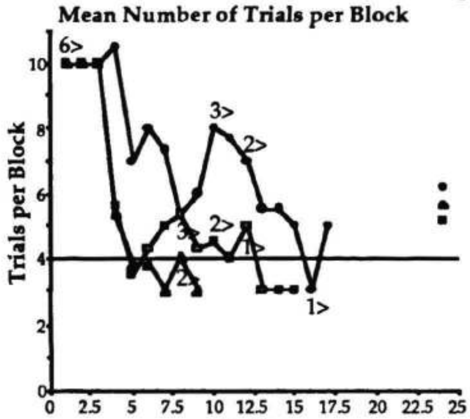
The number of trials and mean movement time for each block of trials were computed for each participant. Based on these results, the data of two participants were removed from the analysis. One male exhibited much slower and more variable times and an exceptionally large number of trials per block compared to the other participants. He was discovered to be left hand dominant. The other was a female who exhibited a distinct lack of motivation while performing the task. Her criterion time was very slow and was found not to be representative of her performance capabilities as revealed in a number of other blocks from baseline and experimental trials. Her data also exhibited an unusually high degree of variability.

Mean movement times and the mean number of trials per block were calculated for the remaining 6 participants. The overall mean criterion time for the 6 participants was 1.1 s (sd=.053 s).

Movement times decreased over trials within blocks. In the first prism blocks on the first day, times started well above criterion and dropped to criterion levels over an average of about 11 trials. In the first clear goggles block following this, times dropped to criterion in about 7 trials. These results were consistent with the standard "adaptation" pattern, including the asymmetric number of trials with and without the prism. However, the amount of decrease in times over trials within blocks itself decreased over successive blocks as did the initial amount of time above criterion at the beginning of blocks. These changes in times revealed that the pattern of results with initial exposure to the prism was merely the first stage in a process of perceptuomotor skill acquisition.

Mean movement time and the mean number of trials per block decreased over successive blocks within a session. In addition, mean movement time and the mean number of trials per block decreased across days. The variability in movement times followed a similar trend showing that participants were performing the task with increasing consistency as well as proficiency.

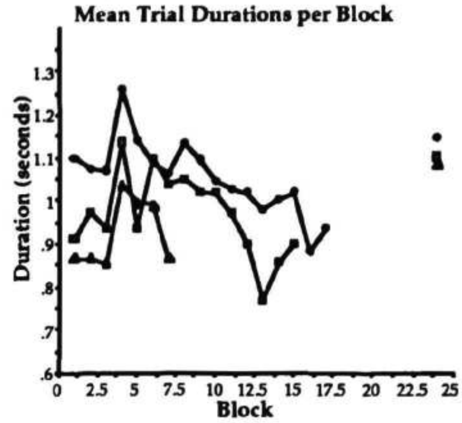
The mean number of trials per block is shown in Figure 1 for the 3 days (Day 1: filled circles; Day 2: open squares; Day 3: filled triangles). As required by design, the number of trials for the first three baseline blocks (binocular, monocular, and clear goggles 1) remained constant across days at 10 trials. After a slight increase for the first prism block on day 1, the mean number of trials for each subsequent block declined progressively in a nonmonotonic fashion. Mean number of trials to criterion dropped below 4 trials after 14 alternating blocks on day 1. Some participants reached the 4 trial cutoff before others. The number of participants contributing to the means was shown in Figure 1[1].



A similar pattern was obtained on day 2, although the mean number of trials in the first prism block was only 5.67, a drop of 4.83 from day 1. This drop also was evident on day 3 in which a mean of 5.33 trials was required to reach criterion in the first prism block. The total number of alternating blocks performed before the cutoff on day 2 was 12, however, the 9-12th blocks were performed by a single participant. For day 3, the number of alternating blocks was 6. The overall mean number of trials to criterion per block dropped over days from 6.5 on day 1 to 4.2 on day 2 to 3.8 on day 3.

[1] For instance, 3 participants had reached the 4 trial cutoff by the 9th block overall on the first day, leaving 3 participants contributing to the mean for the 10th block.

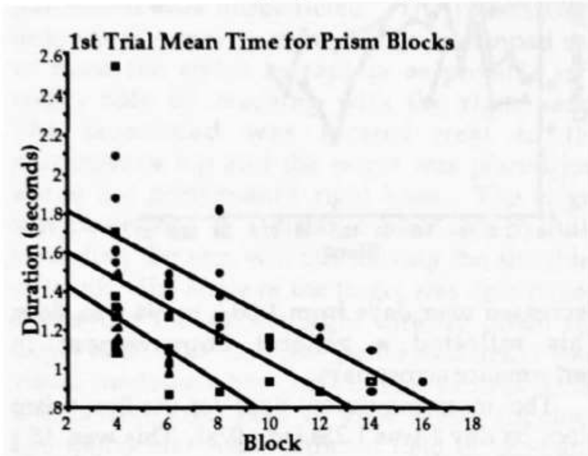
As shown in Figure 2, mean movement times for binocular, monocular, and clear goggle 1 blocks were similar to one another on all 3 days. However, the overall mean time for these blocks



decreased over days from 1.08 s to .94 s to .86 s. This reflected a general improvement in performance across days.

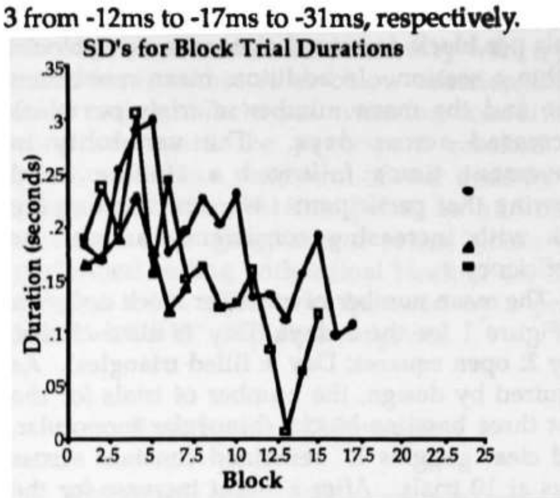
The mean movement time for the first prism block on day 1 was 1.25s (sd=.07s). This was .18 s greater than the mean of the clear goggle 1 block. This increase was exactly the same each day. Prism 1 mean times for days 2 and 3 were 1.12 s and 1.04 s, respectively.

However, subsequent rates of decrease of mean times over blocks were different on different days. We performed linear regressions on the individual times for the first trial of each block from prism 1 on to the last clear goggle block (that is, excluding the 15° prism blocks), regressing block number on times for each day. All 3 regressions were significant, $p<.01$ or better. The slopes represented the decrease in mean time per block. Over days, the slopes increased from -15ms to -47ms to -113ms. When coupled with the mean prism 1 times, these results mean that, on subsequent days, participants started with faster times and proceeded to decrease more rapidly from those times over blocks. However, the change in the rate of decrease occurred only for clear goggle blocks. The result of a linear regression of block number on individual times for the first trials of prism blocks alone was plotted in Figure 3. Almost identical slopes were obtained for all 3 days. The slopes were -69ms, -71ms, and -84ms for days 1-3 respectively. This means that the movement time for the first trial of prism blocks decreased at a constant rate of about 70ms per block on all 3 days. The difference in intercept between days 1 and 2 was 220ms (≈3x70ms). Between days 2 and 3, it was 140ms (=2x70ms). This means that about 3 prism blocks worth of progress (or about 1+3=4, 4x2=8 prism/clear goggle alternations) was retained on the second day, while about 3 prism blocks worth of progress beyond day 2 (or about 6 prism/clear goggle alternations) was retained on day 3. The regularity in these numbers surely implies the existence of an underlying learning function.



The mean times for the final 15° prism blocks all hovered around the mean criterion time across participants implying that the participants discovered exactly what this time was and tended to optimize to that time. Mean times for 15° prism blocks were less than or equal to those for the first 10° prism blocks on a given day. Because 15° prism trials were performed after participants had re-adjusted to the clear goggle condition, we can infer that skill gained in the context of adjustment to 10° prisms was used to advantage in adjusting to a 15° prism[2]. In the learning literature, this would be called "positive transfer" or "stimulus generalization" (Welch, 1978; 1991).

Finally, the standard deviations for block times were plotted in Figure 4. Variability in movement times decreased over blocks within a day. Further, the rate of decrease from a common initial level of variability increased over days. Linear regressions were performed on standard deviations for blocks starting with prism 1 (and excluding 15° prism blocks), regressing block number on SD's. The slopes increased over days 1-3 from -12ms to -17ms to -31ms, respectively.



Thus, participants exhibit approximately the same amount of random variability at the beginning of subsequent days. Reduction of this variability preceded more rapidly on successive days. The implication is that participants start with a rough form of the adjustment function on a given day, but proceed with skill to hone in quickly on a stable adjustment function.

Conclusions

We found evidence for processes on multiple time scales including individual reaches performed in about 1 second, adjustment to perturbation over trials within a block occurring over about 1 minute, acquisition of the ability to adjust over a mere couple of trials occurring over 1 hour, and acquisition of the ability to adjust almost immediately on first exposure, which occurred over days. The problem, viewed in the light of this evidence, is to find a common framework enabling us to understand how processes on different time scales can interact and determine one another.

Another, perhaps more familiar way of expressing this question is as follows. We have evidence that adjustments to perturbations by displacement prisms are part of a process of sensorimotor skill acquisition. The questions that arise naturally in this context are: What are the old skills? What are the new skills? How are the new skills related to the old skills?

Our experiments provided us with kinematic data that we can use to begin to address these questions. We will turn to this task in future papers.

[2] Although, participants were not as quick to adjust as they were on the immediately preceding 10° prism block.

Acknowledgments

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