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The Rate of Adaptation to Displacement Prisms Remains Constant Despite Acquisition of Rapid Calibration

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Acquisition of rapid calibration of reaching with displacement prisms was studied. Participants reached rapidly to place a stylus in a hole. Blocks of trials with and without a 10° displacement prism were alternated over sessions on 3 days. Movement times (MTs), peak velocities (PVs), and path lengths (PLs) of reaches were measured. MTs and PLs increased at the beginning of blocks and then decreased over trials within blocks. The rate of adaptation within blocks did not change over blocks or days. Initial increases in MTs and PLs at the beginning of blocks gradually decreased. Progressively fewer trials were needed to reach criterion MTs. Calibration was nearly immediate by Day 3. The authors discuss visual information used for calibration.

Calibration[1] is essential to perceptually guided actions like reaching or throwing for two related reasons (Bingham & Pagano, 1998). First, calibration is needed to maintain the stability of perceptual measurements. Researchers have found that targeted reaches drift and become more variable without either visual or haptic feedback, but when haptic feedback from contact with targets is allowed, reaches become stable and more accurate (Bingham, Flascher, & Zaal, 1997; Bingham & Zaal, 1997a, 1997b; Bingham, Zaal, Robin, & Shull, in press; Flascher, Zaal, & Bingham, 1997; Wickelgren, McConnell, & Bingham, 1997). This instability is not unique to reaching or due only to motor variability. Direct comparisons of verbal judgment and reaching measures of distance perception have shown that verbal judgments are at least twice as variable as reaches (Foley, 1977; Pagano & Bingham, 1998) and that the variability is reduced and accuracy improved by feedback (Ferris, 1972; Pagano & Bingham, 1998).

A second reason calibration is essential to perceptually guided actions is the need to be able to respond efficiently and effectively to perturbations (Reiser, Pick, Ashmead, & Garing, 1995). The most common example of this need is the wearing of corrective lenses, which alters magnification and sometimes visual direction. A somewhat more exotic example is spear fishing, in which the visual direction and magnification of a targeted fish is altered by viewing it from above the surface of the water. In both cases, success in targeted action requires calibration.

The largest body of calibration research is on the response to perturbations of visual direction, that is, studies of adaptation to vision through wedge-shaped displacement prisms (see Howard, 1971; Kornheiser, 1976; Redding & Wallace, 1997a; and Welch, 1978; for reviews). Typically, observers wearing displacement prisms first reach in the direction of displacement. Over a series of trials, reaches are gradually corrected and become accurate. With subsequent removal of the prisms, observers initially reach to the opposite side of the target and then become correct, usually over fewer trials than required for the original adjustment.

The problem with this adaptation process is that it is slow. The adjustment typically requires 10–15 reaches to become accurate. If generalized to the case of spear fishing on a lake, this rate of adjustment would mean the loss of 10–15 fish before success in catching dinner, assuming the fish stay long enough to be caught. More to the point, when one first wears corrective lenses, one experiences some disorientation

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[1] Calibration establishes a mapping between units of two measurement systems (Rosen, 1978). Any given measurement returns a value in some unit. Typically, for the information to be useful, the measured units must be related to other known units. For instance, lengths measured with a stick might be related to the foot or meter. Also, lengths along a level plane measured from a fixed locus above the plane as an angle between a sight line and the plane might be related to a person's stride length. Calibration is itself measurement and, so, entails a functionally determined tolerance used to establish accuracy (see Bingham, 1987; Bingham & Pagano, 1998; and Bingham, Zaal, Robin, & Shull, in press, for extended discussion). In the current research, calibration entails a relation between the visually determined (i.e., using optics, somatosensation, and coordinated actions of the head) location of a target and the location determined by reaching (i.e., using vision of the hand and target, somatosensation, and coordinated actions of the hand).

and clumsiness that gradually fades. The experience is onerous, and if it happened every time a person tried to use corrective lenses, then he or she might well abandon the lenses. Nevertheless, people are eventually able to don and doff their glasses with immediate adjustment and no experience of awkwardness. While the majority of research on prism adaptation has focused on the initial slow change, researchers have recognized an eventual ability to adjust rapidly.

In discussing *double localization* results obtained in studies on perturbed auditory localization, Richard Held (1965) suggested that participants might acquire "a new mode of coordination that is objectively accurate for the condition of rearrangement but that coexists along with the older mode" (p. 89). Similarly, Herbert Dolezal (1982) suggested at the end of his study on inverting prisms that the practiced participant might become "biperformatory" and "biperceptual" (pp. 291–297), meaning that the ability to perform accurately while wearing the prism would coexist with the ability to perform without it. In contrast, Welch (1986) suggested that with repeated exposure, observers might acquire *learning sets,* which he defined operationally as an increase in the rate and/or extent of adaptation that results from repeated exposure to prismatic displacement. These alternatives raise the following question: If observers do acquire an ability to make rapid adjustments, does this entail a change in the rate of adaptation or, instead, the acquisition of a new mode of performance? That is, would rapid adjustment be achieved by adapting at a faster rate or by replacing the process of adaptation with another faster process?

Previous research has explored change in adaptation or aftereffect (Flook & McGonigle, 1977; Lazar & van Laer, 1968), as discussed by Welch (1986), who judged these studies as inconclusive. More recently, Welch and his colleagues investigated the acquisition of "learning or adaptation sets" under conditions of repeated exposure to a prism (Welch, Bridgeman, Anand, & Browman, 1993). However, their study used pointing error before, during, and after exposure as the measure of adaptation. This measure is problematic if the object of investigation is the potential change in the rate of adaptation.

Measuring Times and Trajectories Versus Endpoint Error and Aftereffect

Since the mid-1960s, the standard method for studying adaptation has been to measure error in pointing while the participant looks at a target but is unable to see the hand with which he or she points. This measurement is performed before exposure to the prism and then after exposure, and the difference in error is used as the measure of adaptation. The exposure task is to point at targets with vision of the hand. The use of pointing errors during exposure to obtain information about the rate of adaptation introduces a potential problem: The participant may be partially correcting his or her pointing on-line, that is, during the reach.

Using pointing error as a measure of adaptation during exposure would entail an instruction not to correct the reach, despite visibility of both the target and the reach. Adaptation is known to require observation of one's activity while trying to perform a targeting task (Held & Hein, 1958; Redding & Wallace, 1990, 1992, 1996, 1997a; Welch, 1978). It is necessary to have information about the change in visual direction and its effect on reaching. When first exposed to a prism, one normally succeeds in reaching to a target using on-line visual guidance, although the reach might take a little longer. It was once believed that on-line guidance of a reach was restricted to the final, slower movement phases of target acquisition. However, a large number of double-step targeting experiments have shown that reaches are visually guided throughout a reach and that this need not require vision of the hand (e.g., Flanagan, Ostry, & Feldman, 1993; Goodale, Pelisson, & Prablanc, 1986; Jeannerod & Marteniuk, 1992; Martin & Prablanc, 1991). The effect on reaches of instructions not to correct is unclear, and the extent to which such interference is successful in preventing on-line correction is unknown.[2] An alternative method of measurement would be to allow each reach to follow its normal course to acquire a target and then to measure changes in its temporal and spatial efficiency. Adaptation would gradually diminish the perturbing effect on the initial phases of a reach, and the need for large corrective feedback would change. Studies of both Jakobson and Goodale (1989) and Rossetti, Desmurget, and Prablanc (1995) have successfully used such measures of adaptation.

We used this alternative approach in the current study. To simplify the measurements, we used a targeted reaching task that did not involve grasping but did entail contact with the target and associated constraints on accuracy. We used a placing task that was spatially and functionally well specified and representative (e.g., placing a key in a lock, a book on a shelf, or mail in a slot). We measured times for maximally fast reaches to place a peg in a hole and used time as both our measure of performance and our criterion of successful adjustment. Reaches were first performed without a prism to establish a criterion time; then participants wearing a 10° displacement prism struggled to regain their previous prowess in speed. Once this was accomplished, the prism was removed and participants once again worked against the aftereffect to achieve their criterion time. Blocks of trials with and without the prism were alternated until participants were able to reach criterion times immediately on application of the prism. We then tested for generalization to reaches performed with a 15° prism. The entire series was performed on 3 contiguous days.

The first goal of this study was to determine whether the number of trials required for adjustment would diminish over blocks of trials. Bingham, Muchisky, and Romack

[2] This might be called a *noninterference* instruction, meaning that one should not use feedback control to interfere with an initial, ballistic feedforward control. But this instruction assumes that one is able to separate aspects of control voluntarily, which may not be possible. Given recent evidence for the role of proprioception in reaching (Cole, 1995; Ghez, Gordon, Ghilardi, & Sainburg, 1995), it is likely that somatosensory feedback control is always operative and that reaches are never truly ballistic.

(1991) performed an initial study involving a single day of trials and found improvements over blocks of trials. The second goal was to determine whether the rate of change over trials within blocks would change over blocks or, alternatively, whether the initial amount of increase in movement time would decrease over blocks. The third goal was to determine whether the rates of change are the same for prism blocks and blocks in which the prism has been removed. The fourth goal was to determine whether these improvements would be retained as savings on Days 2 and 3. The fifth goal was to determine whether the improvements would transfer to reaches performed with a larger 15° prism.

There were two other methodological issues. First, in a departure from standard methods, we allowed free head movements (and measured them), because restriction of head movement is an additional perturbation that becomes confounded with perturbation of visual direction. A well-established and reliable characteristic of visually guided targeting behaviors is that the head is moved to center the target in the visual field (Biguer, Prablanc, & Jeannerod, 1984; Carnahan, 1992; Smeets, Hayhoe, & Ballard, 1996). Perturbation of this head movement lowers the precision and accuracy of targeting (Carnahan, 1992).

The second methodological issue was the need to control for *conscious correction,* that is, an explicit aiming for a virtual target to correct for the perturbation of visual direction (Harris, 1965). The aftereffect measure was originally developed, among other reasons (Held & Gottlieb, 1958), to control for conscious correction. We explicitly instructed participants not to use this strategy. They were told to aim directly for the target and to do their best to fit the peg into the hole.

We tested for participants' compliance in two ways. First, performance improves suddenly with explicit correction, so the gradualness of transitions has been used as evidence of the absence of a cognitive strategy (Droulez & Cornilleau, 1986). In addition to movement time, we measured and analyzed the three-dimensional kinematics of the reaches, including peak velocity and normalized path length. The latter is a measure of spatial efficiency. We examined changes in movement time, velocity, and path length for the gradualness of transitions. Second, the presence of an aftereffect has also been used as a criterion for the absence of a cognitive strategy (e.g., Droulez & Cornilleau, 1986; Harris, 1963). We were effectively able to measure the aftereffect in terms of increases in movement time and path length each time the prism was removed. Such increases would reveal an aftereffect and therefore would show, according to standard methodology, that adaptation was indeed taking place. Jakobson and Goodale (1989) found such aftereffects in reaches performed when the prism was removed after adaptation (see also Rossetti et al., 1995). These researchers and others (Uhlarik, 1973) have found that the amount of aftereffect is reduced when participants are aware of the presence of the prism, but, as pointed out by Jakobson and Goodale, this does not imply the use of conscious correction. Rather, participants tend to be more vigilant in the use of continuous visual guidance to complete a reach (Elliot & Allard, 1985; Jakobson & Goodale, 1989). Redding and Wallace (1996, 1997a, 1997b) have also found that the use of feedback control reduces the amount of aftereffect.

The central question was whether both the rate of adaptation to a prism and the rate of readaptation when the prism is removed remain invariant over repeated application of a prism and its removal, or whether the acquisition of more rapid adjustment involves a change in the rate of adaptation.

Method

Apparatus

All reaches were measured using a two-camera WATSMART system, which samples 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 a trigger housed in a launchpad and in the target. Data collection routines were initiated when a stylus was removed from the launchpad and terminated when the stylus was inserted into the target. Placement of the stylus in the launchpad broke an infrared beam, which set the clock to 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 that stopped the clock. Movement times were displayed on a cathode ray tube (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 high × 4-cm wide piece of Plexiglas, which supported three IREDs that were placed above, below, and to the right of the eye. One pair of goggles was covered only with Plexiglas, the other two sets of goggles had displacement prisms mounted over the Plexiglas on the right eye. Visual displacement was 10° and 15° to the right, respectively.

Participants

Five right-handed adults, 3 male and 2 female, ages 18–28 years, participated in this experiment. All participants had good, uncorrected vision and had never worn corrective lens. All were free of motor disabilities. Participants were paid $5/hr for their participation in the study.

Procedure

Three experimental sessions were performed on consecutive days at approximately the same time each day. During testing, participants were seated comfortably. Head movement was unrestricted. The participants' task was to remove a stylus from a launchpad and to place the stylus as quickly as possible into 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 and to the inside of 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 asking the participant to sight directly down the target hole. This hole was 1 cm in diameter and lay in the center of a wooden disk that was 6.6 cm in diameter. The stylus was 0.9 cm in diameter and 24 cm in length. A small collar was attached at a distance of 5 cm from each end of the

stylus to constrain the length of insertion into the launchpad and target, respectively. The back end of the stylus was placed into the launchpad while the front end was inserted into the target so that reaches proceeded smoothly from one to the other without reversing direction of movement and without large rotations of the stylus. The stylus was held in a power grip, with the thumb placed immediately behind the front collar. The task was performed under five visual conditions. The first two conditions were practice conditions: binocular and monocular. No goggles were worn. A patch was worn over the left eye in the monocular condition. The next condition was monocular with a restricted field of view. This was called clear goggles (CG) because participants wore the goggles mounted with only the Plexiglas. The last two conditions were both monocular with restricted field of view and displaced vision. The displacement was either 10° (called prism-10 or P10) or 15° (P15). The numeral following CG or P10 represents the number of the block, as CG and P10 blocks were alternated, always beginning with a CG block. A single P15 block followed each day's session.

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

The first two blocks consisted of 10 practice trials in each of the binocular and monocular conditions. The remainder of the experiment consisted of alternating blocks of CG and prism trials. The initial CG block consisted of 10 trials, which were used to obtain each participant's criterion value. The participants were not aware at this point that a criterion time was being measured for use throughout the remainder of the experiment. The criterion value was determined by taking the mean of each 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 each participant to reach the criterion value in three consecutive trials. Participants were informed that they were trying to achieve reaches at or below criterion times. Alternating blocks of CG and P10 viewing conditions continued until each participant reached the criterion within a maximum of four trials for the prism condition. At this point, an additional CG block was performed, followed by a P15 block. The entire sequence from binocular to P15 was the same on each one of the 3 days.

Data Processing

The 3-D trajectory data for the head and hand were digitally filtered with a second-order Butterworth filter that was applied twice in opposite directions to prevent aliasing. The filtered position data were differentiated using a central difference algorithm to derive velocities. We used x, y, and z velocities to compute the tangential velocity of the hand. Peak tangential velocities were picked as the simple maxima of the velocity curves.

Path lengths traveled by the hand were computed by determining the 3-D distance traveled between samples and summing distances along the trajectory. Gaze angle was computed as the angle in the transverse plane of the head between the line from the eye to the target and the line perpendicular to a plane determined by the three IREDs on the goggle.

We computed spatial means of trajectories as follows: A coordinate transform was performed to move the origin of the Cartesian system to the target. The 3-D distance between the launch platform and the target was divided into units of 0.1 mm, and these units were used to index the trajectories and to bin the samples. We divided the distance in small units to ensure that two sample points would not be placed into a single bin. For each trajectory, each sample point was placed into the bin corresponding to its straight line distance to the target. For each trajectory, bins intervening between those filled with sample points were filled by use of a linear spline. Averages and standard deviations were then computed for each bin to derive mean trajectories for each block of trajectories.

Results

All statistical analyses were performed on the data of the first eight blocks each day, starting with the first P10 block. Thus, four P10 and four CG blocks were included.

Analysis of Movement Times

Criterion times were computed for each participant from CG 1 time on Day 1. The overall mean criterion time for the 5 participants was 1.04 s (SD = 0.13 s).

As shown in Figure 1, movement times decreased over trials within blocks. In the first prism block on the first day, times started well above criterion levels and dropped to criterion levels over an average of 10 trials. In the first CG block following the first prism block, times dropped to criterion levels in about 7 trials. The initial amount of time above criterion levels also was less in this second CG block than in the first prism block.

As also indicated in Figure 1, the number of trials per block decreased over successive blocks on all 3 days, as well as over days. The mean number of trials required to achieve criterion levels in the first prism block dropped from 10.2 on Day 1 to 5.2 on Day 2 and to 5.6 on Day 3. The mean number of trials for the second CG block dropped from 7.4 on Day 1 to 3.6 and 4.0 on Days 2 and 3, respectively. Combining the data for the 5 participants, we performed a multiple regression, regressing block number, a day number, and an interaction vector on the number of trials in each block for each participant. The result was significant, but the interaction vector was not significant (partial $F < .5$), implying that the rate of decrease was the same each day. We performed the analysis again without the interaction vector. This second analysis yielded an R^2 of .28, $F(2, 84) = 16.1$, $p < .001$. Block number was significant, partial $F(1, 84) = 4.9$, $p < .03$. The number of trials per block decreased at the average rate of .30 trials per block. Day number also was significant, partial $F(1, 84) = 31.0$, $p < .001$. The number of trials per block decreased on average by 1.9 trials per day. The number of blocks required to reach a criterion of only 4 trials per prism block (including 3 below the criterion time) decreased over days until all participants were completing the session in 3 pairs of alternating blocks or less.

The question was whether this drop in the number of trials per block was produced (a) by a progressive increase in the rate of decrease in movement times over trials within blocks (i.e., Were participants adapting at a faster rate within blocks?), or (b) by a decrease in the size of the initial increase in movement time at the beginning of each block (i.e., Was the change in viewing condition progressively less

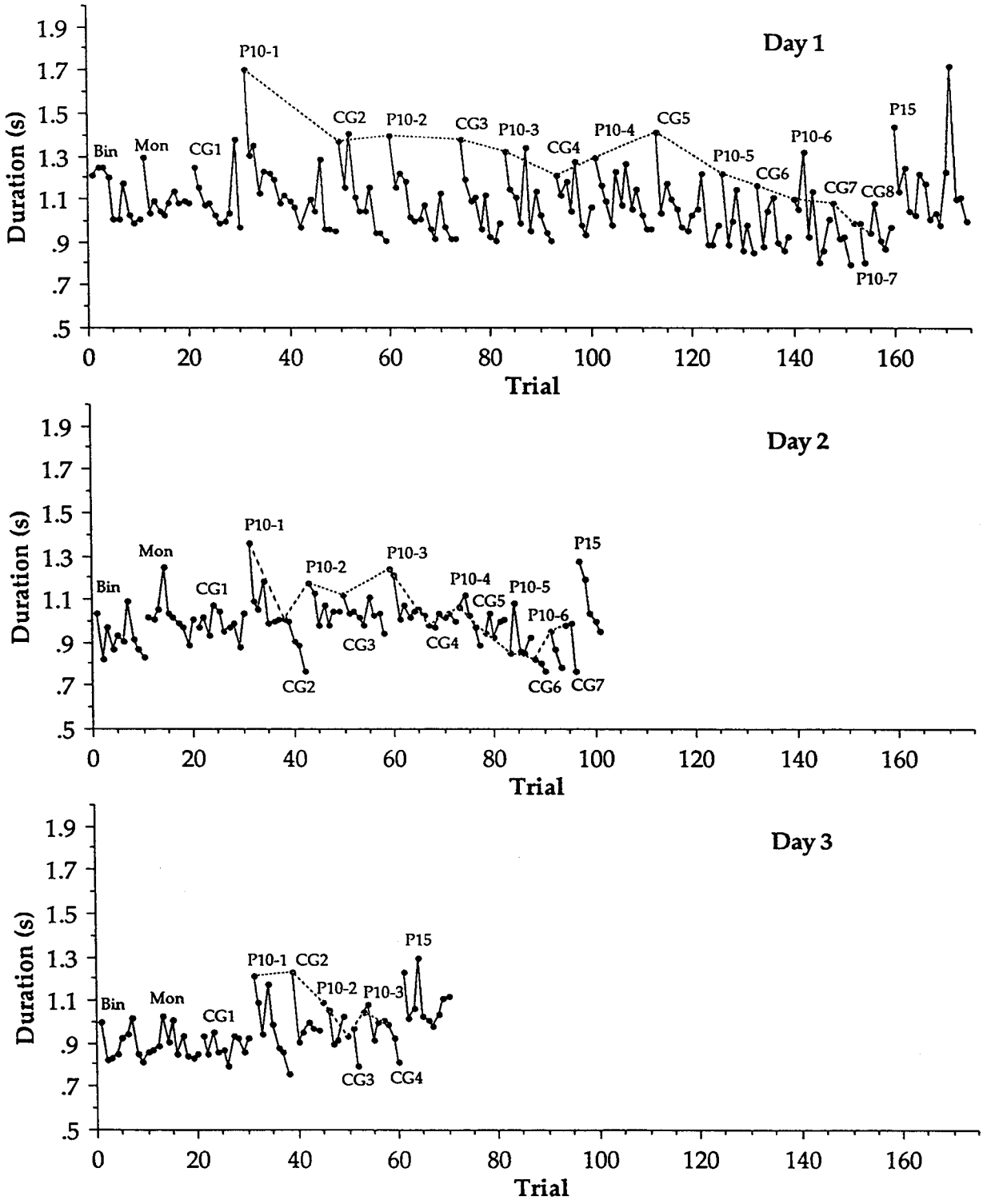

Figure 1. A graph for each session on 3 successive days. Mean movement times for each trial within blocks of binocular viewing (Bin), monocular viewing (Mon), clear goggle viewing (CG), viewing with 10° prismatic displacement (P10), or viewing with 15° prismatic displacement (P15). The dotted line connects mean times for the first trial in each successive P10 or CG block.

perturbing?). Mean movement times per block decreased over blocks and days for both prism and CG trials. This pattern replicated the result obtained for the single day in a previous study (Bingham et al., 1991). The decrease occurred primarily because the times for the first trial in each block decreased over blocks and days, as shown in Figure 1.

We performed separate analyses on P10 and CG movement times. In each case, we simultaneously regressed trial number (within block), block number (within day), day number, and interaction vectors on the combined movement times for all participants. For P10 times, the R^2 with all variables entered was .29. Using a procedure described by Pedhazur (1982), we removed all nonsignificant variables one at a time, in order of the smallest partial F. The final result was significant, $F(3, 258) = 34.3$, $p < .001$, with an R^2 of .28. The significant factors were trial, partial $F(1, 258) = 70.1$, $p < .001$; block, partial $F(1, 258) = 18.2$, $p < .001$; and day, partial $F(1, 258) = 65.3$, $p < .001$. Movement times decreased at average rates of 29 ms over trials, 46 ms over blocks, and 121 ms over days. The rate of change of movement times over trials within blocks did not change over blocks or days. This slope remained constant, although the intercept changed over blocks and days.

The same analysis on CG times produced an R^2 of .22 with all factors entered and a final R^2 of .20 with only significant factors, $F(2, 225) = 28.4$, $p < .001$. The only significant factors were trial, partial $F(1, 225) = 29.0$, $p < .001$, and day, partial $F(1, 225) = 48.4$, $p < .001$. CG movement times decreased at average rates of 31 ms over trials and 123 ms over days. Again, the rate of change of movement times over trials within blocks remained constant over blocks and days. The slope remained constant, but the intercept changed over days.

Because these analyses indicated that adaptation rates were not increasing, we then examined the pattern of movement times for the first trial in each block. As shown in Figure 2, the mean first trial times in P10 blocks decreased over blocks on each day at the same rate. Using the data of all participants, we performed a multiple regression, regressing block number, a day number, and an interaction vector on first trial times in P10 blocks. This yielded an R^2 of .55, but the interaction vector was not significant. The result when the analysis was performed again without this vector was $F(2, 41) = 24.5$, $p < .001$, $R^2 = .54$, with both the block, partial $F(1, 41) = 20.3$, $p < .001$, and day, partial $F(1, 41) = 39.3$, $p < .001$ variables significant. Movement times decreased on average by 114 ms per block and by 193 ms per day. This decrease of 193 ms per day with a 114-ms rate of decrease per block meant that improvements achieved over 1.7 blocks were retained on each subsequent day.

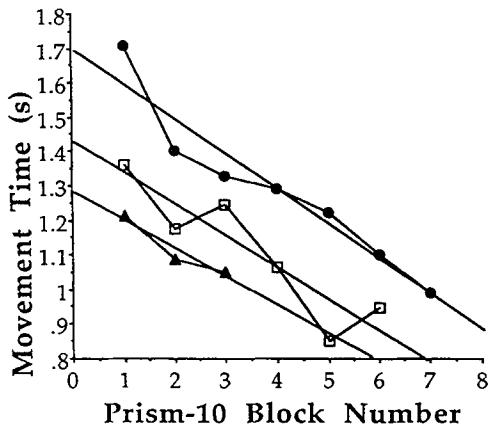

Figure 2. Mean prism first trial times plotted with regression lines for sessions on each of 3 successive days. Day 1 = filled circles; Day 2 = open squares; Day 3 = filled triangles.

When we performed this analysis on first trial movement times from CG blocks, the R^2 was .32, $F(2, 40) = 9.4$, $p < .001$, and both the block variable, partial $F(1, 40) = 5.1$, $p < .03$, and the day variable, partial $F(1, 40) = 16.6$, $p < .001$, were significant. The average decrease in CG first trial times was 68 ms per block and 146 ms per day, for a savings of about 2 blocks worth of change per day. A regression performed on first trial times for both P10 and CG data yielded an R^2 of .48, and the viewing condition variable as well as the block and day variables were significant. On average, CG first trial times were 72 ms less than those for P10 first trials.

To summarize, movement times increased at the beginning of each block, both with the application of the prism and its removal. Times decreased within blocks of trials, finally reaching criterion values. The number of trials required to reach criterion times decreased over blocks within a session on a given day. The most important result was that this decrease was not produced by an increase in the rate of adjustment over trials within blocks. Rather, the decrease in the number of trials required to reach criterion times was a result of a progressive decrease in the first trial times in each block. That is, the size of the response to the perturbation decreased over blocks. Approximately two blocks worth of the decrease in first trial times was retained on each successive day until, by the third day, participants were able to achieve criterion times almost immediately.

The multiple regressions performed on data of all trials yielded different estimates of changes between blocks than did the regressions performed on the first trials. This finding reflected the fact that the linear model provided an imperfect estimate of the behavior within blocks. Examination of the means shown in Figure 1 reveals trends within many blocks that are better estimated as exponential. We had used linear fits because we could not obtain good curvilinear fits to all of the data. Nevertheless, we did find that the mean times for the first few P10 blocks and the P15 block on each day did afford good exponential fits.

We used the following model:

$$T_M = ae^{(bN)} + c,$$

where T_M is movement time, N is trial number within a block, b and a are rate constants, and c is the asymptote of the exponential, or an estimate of the floor approached by trial times at the end of a block. Once we obtained values for a, b, and c, we evaluated the size of the response to the perturbation independently of the floor times by calculating

ae^b (that is, the T_M function at $N = 1$ and $c = 0$). This result reflected the increase in movement time above the floor for the day. We also determined the initial rate of decrease in times from the first trial by evaluating the first derivative of the model (i.e., bae^{bN}) at trial $N = 1$.

The mean R^2 for these exponential fits was .64 (SD = .21), which was better than the mean R^2 for linear fits, .45 (SD = .18). The resulting estimates of the responses to perturbation, the final or floor times, and the initial rates of decrease in times are shown in Figure 3. Consistent results were obtained across 10° and 15° prism trials. The floor times decreased only slightly over days. Initial rates of decrease in times remained fairly steady over blocks or over days and, if anything, tended to decrease on Day 3. This finding confirmed the conclusion from the earlier linear analysis. The rate of adaptation did not change over blocks or days. The clear locus of change was in the initial response to perturbation, which decreased for P10 trials over blocks and days. The result for P15 blocks indicated a decrease in response that was less than the decrease for P10 blocks.

Indeed, as shown in Figure 1, the mean first trial time and the number of trials to criterion time for the P15 were less than that of the first P10 block but greater than that of the last P10 block on the first day. Using the first P10 block, the ratios of P15 over P10 values for mean first trial time, number of trials, and mean block time were 0.84, 0.66, and 0.97, respectively, on the first day. These results replicated those of Bingham et al. (1991), which were 0.81, 0.62, and 0.92, respectively. When computed with the last P10 block for each participant, the results for our study were 1.07, 1.80, and 1.07, respectively, and 0.97, 1.71, and 1.02 for Bingham, Muchisky, and Romack. Overall, these results demonstrate incomplete transfer of improvement in adjusting to a prism. For instance, the number of trials to criterion was reduced by approximately 40% for the P15 when compared with the first P10 block, but the number was increased by 70% when compared with the last P10 block.

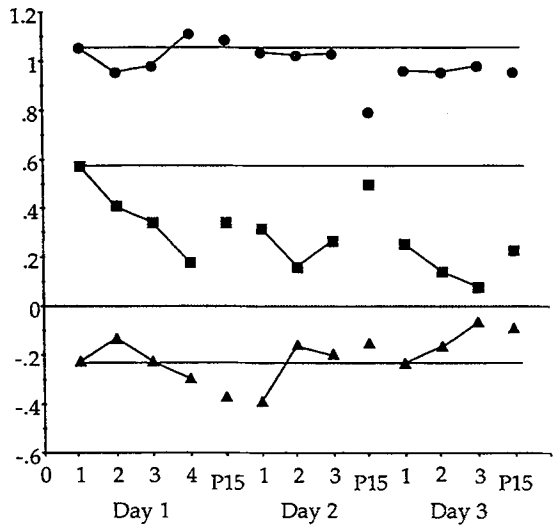

Figure 3. Results of exponential fits to mean movement times for the first 3–4 10° prism blocks and the 15° prism blocks on Days 1–3. Values for c (asymptote of the exponential curve) in seconds (filled circles); values for the first term of the model evaluated at Trial 1, that is, distance above c in seconds (filled squares); values for the first derivative evaluated at Trial 1, that is, initial rate of decline in seconds per trial (filled triangles). In each case, a horizontal line is drawn from the value of the first trial on Day 1 for comparison. P15 = 15° prismatic displacement.

The number of trials, the mean block time, and the mean first trial time all decreased over days for the P15 blocks. However, the ratios comparing P15 and P10 results increased progressively and in like manner for all three measures. For instance, for first trial time, the ratio with the last P10 block increased over days from 1.07 to 1.14 to 1.19, and the ratios with the first prism block increased from 0.84 to 0.94 to 1.02. The implication of these results is that although there appeared to be some transfer of improvements, there may be an additional time scale involved in the generalization of skilled adjustment to prisms of varying size. This finding would be consistent with the fact that some period of adjustment is required when a new prescription is obtained, even for an experienced user of corrective lenses. However, some individuals are eventually able to adjust rapidly to corrective lenses of different power (Bradley, personal communication, 1992).

Analysis of Reaching Kinematics

Next we turned to an analysis of the reach trajectories to determine whether gradual changes occurred in the trajectories parallel to the gradual changes in movement times. Representative trajectories, shown in Figure 4, are projected on the horizontal x–y plane. As illustrated by the mean trajectory from the first CG block, participants with unperturbed vision followed a direct route to the target in the horizontal plane. Also shown is the first reach performed while viewing the target through the 10° prism. Characteristically, this trajectory veered in the direction of the visual perturbation. Subsequently, the trajectory headed back toward the actual target location once again, eventually ending at the target. Velocity tended to be reduced, especially during the latter correction phase. The third trajectory shown in Figure 4 illustrates the behavior during the first reach following removal of the prism at the beginning of the second CG block. There is clear evidence of an aftereffect. This trajectory deviated in the direction opposite the prism perturbation and veered back toward the actual target location near the end of the trajectory. Velocity tended to remain high along the majority of the trajectory. These observations are consistent with the results of Jakobson and Goodale (1989).

We observed that the tendency to veer away from the direct trajectory diminished over trials within blocks, over blocks, and over days. We computed path lengths as a measure of the effect of the visual perturbations on trajectories. We computed normalized path lengths by dividing path lengths by the initial distance to the target. The resulting measure revealed the relative inefficiency of movement as the amount by which values exceed 1. The perturbed trajectories entailed greater path length than did the unper-

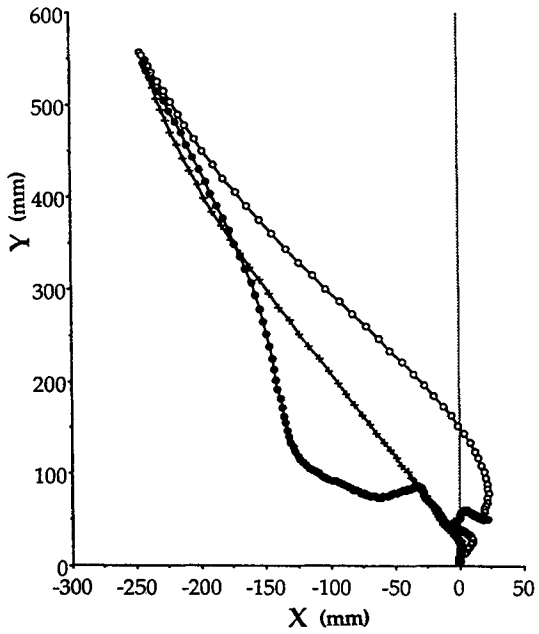

Figure 4. Paths of hand movement projected in the horizontal *x*–*y* plane. Representative trajectories are shown for one participant. The target is at (0, 0). *CG1* block mean = crosses; the first trial from the *P10-1* block, that is, the first prism trial = filled circles; the first trial from the *CG2* block, that is, the first trial after the prism has been removed = open circles. CG = clear goggles condition.

turbed trajectories. As the size of the response to the perturbation diminished, so, too, did the path length. Mean normalized path lengths are shown in Figure 5. Path lengths increased at the beginning of prism and CG blocks and then diminished over trials within a block. The size of the increases at the beginning of the blocks decreased over blocks and over days. The increases were larger for CG blocks because the hand traveled larger distances, starting from the right and overshooting to the left of the target and then returning.

As we did for movement times, we performed multiple regressions, regressing trial number, block number, day number, and interaction vectors on normalized path lengths, with separate analyses for P10 and CG data. For P10 data, the R^2 with all factors included was .14. With only the significant factors included, $R^2 = .13$, $F(3, 258) = 13.1$, $p < .001$. The significant factors were trial, partial $F(1, 258) = 17.1$, $p < .001$; block, partial $F(1, 258) = 20.6$, $p < .001$; and day, partial $F(1, 258) = 22.0$, $p < .001$. For clear goggle data, the R^2 with all factors included was .21. With only the significant factors included, the $R^2 = .19$, $F(3, 224) = 18.0$, $p < .001$. The significant factors were trial, partial $F(1, 224) = 35.0$, $p < .001$; block, partial $F(1, 224) = 4.9$, $p < .03$; and day, partial $F(1, 224) = 34.1$, $p < .001$. The results in both cases mirrored those for movement times. The rate of change in path length over trials did not interact with block or day; it remained invariant.

Simultaneous regression of block number, day number, and an interaction vector on first trial path lengths also produced the same pattern of results as for movement times. The interaction was not significant in the analysis of P10 data, $R^2 = .35$, $F(2, 41) = 11.0$, $p < .001$, but both block number, partial $F(1, 41) = 13.2$, $p < .001$, and day number, partial $F(1, 41) = 14.0$, $p < .001$, were significant. Normalized path lengths decreased on average by 1.7% each block and by 2.1% each day. Block number, partial $F(1, 40) = 7.3$, $p < .03$, and day number, partial $F(1, 40) = 13.4$, $p < .001$, were also significant in the analysis of clear goggle data, $R^2 = .29$, $F(2, 40) = 8.0$, $p < .001$. The normalized path length decreased on average by 2.1% each block and by 3.8% each day. An analysis performed on the combined prism and CG data was significant ($R^2 = .43$), and in addition to block and day, viewing condition was significant. On average, CG path lengths were 2.5% longer than those in prism blocks.

Direct comparison of results for movement times and normalized path lengths is made in Figure 6, in which mean first trial times and path lengths are plotted together with overall block means for each measure. Strong and rather persistent aftereffect can be seen in the first trial path lengths of the CG condition on Day 1. The strength of this effect diminished significantly in subsequent days. In the multiple regression results, the decrease over days for CG was nearly double that for P10. This effect did not show in movement times that, overall, were more similar in CG and prism data than were path lengths. The implication is that hand velocities were greater for reaches in the CG condition. We computed mean normalized first trial path lengths for each participant and performed a repeated measures analysis of variance (ANOVA) on them, with day and viewing condition as variables. Viewing condition was significant, $F(1, 4) = 20.0$, $p < .02$. CG path lengths were longer than P10 path lengths: CG = 1.13 vs. P10 = 1.08. Day was significant, $F(2, 8) = 6.3$, $p < .03$. Path lengths decreased over days: 1.14, 1.10, and 1.08. The Viewing × Day interaction was significant, $F(2, 8) = 5.6$, $p < .03$. Path length dropped more steeply on Day 1 for CG than for P10: CG = 1.18, 1.11, and 1.11 vs. P10 = 1.10, 1.08, and 1.06.

In the same analysis performed on peak velocities, we found that only the viewing condition variable was significant, $F(1, 4) = 23.0$, $p < .01$. CG velocities were greater than P10 velocities: CG = 209 cm/s vs. P10 = 188 cm/s.

When the analysis was performed on movement times, viewing condition was significant, $F(1, 4) = 25.5$, $p < .01$. CG reaches were faster than P10 reaches: CG = 1.14 s vs. P10 = 1.26 s. Day was significant, $F(2, 8) = 15.2$, $p < .01$. Movement times decreased over days: 1.40 s, 1.11 s, and 1.10 s. Despite longer path lengths, the shorter movement times for CG reaches were produced by significantly greater peak velocities. Nevertheless, the decreases in movement times over days must be attributed to decreases in path lengths, not to increases in peak velocities.

We examined gaze angles, that is, the head orientation relative to the direction from the eye to the target. We lost the data for one participant due to WATSMART errors (reflections off his nose). We report results for the remaining 4

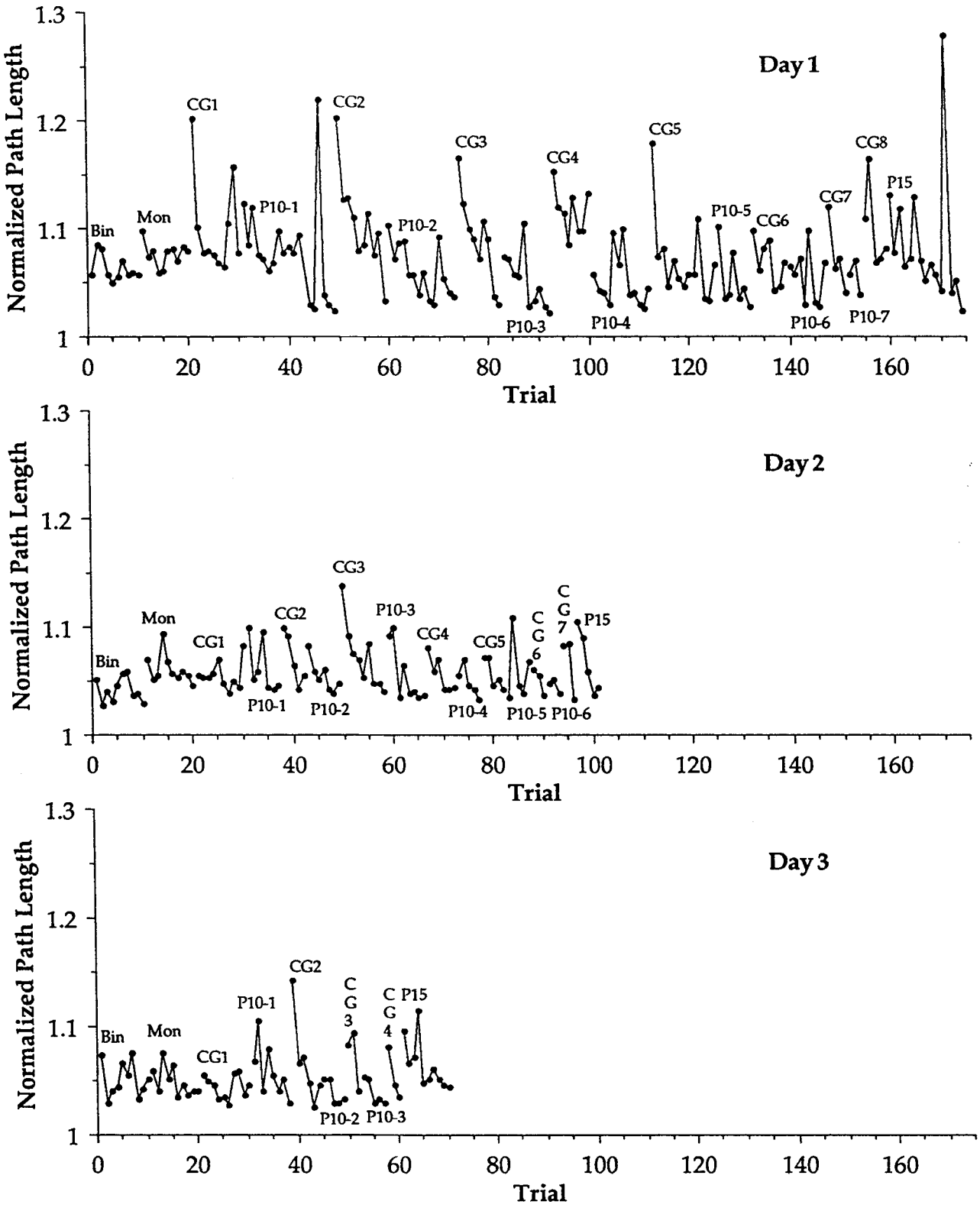

Figure 5. A graph for each session on 3 successive days. Mean normalized path length of reaches for each trial within blocks of binocular viewing (Bin), monocular viewing (Mon), clear goggle viewing (CG), viewing with 10° prismatic displacement (P10), or viewing with 15° prismatic displacement (P15). Path lengths were normalized by dividing by the distance between launch platform and target.

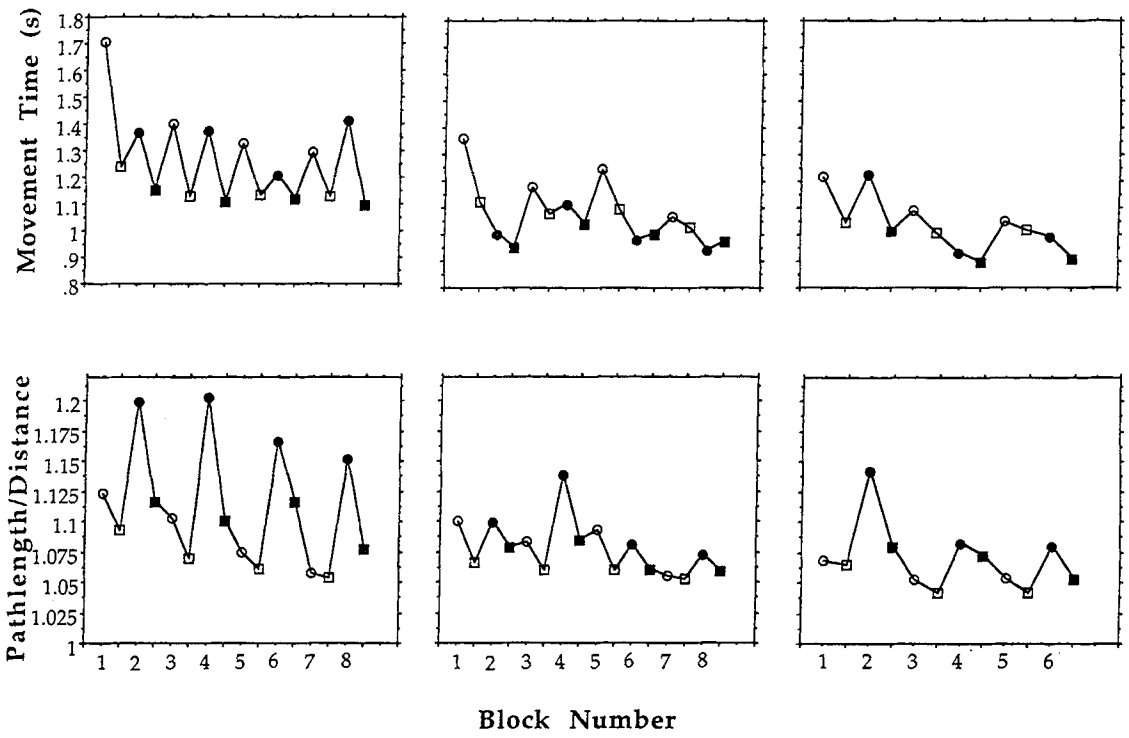

Figure 6. Plots of mean movement times (upper row) and mean normalized path lengths (lower row) for each of the 3 days. Means for the first trial in each block are plotted as circles. Means for the remainder of the trials in each block are plotted as squares. First a circle and then a square is plotted for each of the first eight blocks. Prism means are plotted as open symbols. CG means are plotted as filled symbols. CG = clear goggles condition.

participants. Mean gaze angle trajectories computed for each participant over the first CG block on Day 1 and over the first prism and second CG block on each day are shown in Figure 7. The trajectories are plotted in terms of the momentary distance of the hand from the target (e.g., how the head was oriented when the hand was halfway to the target). In all cases, the participant's head was pointed at the actual target location during clear goggle trials.[3] More important, the head was consistently directed toward the displaced position of the target image in all prism trials. This behavior remained constant on all three days. When wearing the prism, participants always oriented their heads toward the displaced position of the target.

Finally, the movement time and normalized path length results in the CG viewing condition showed that traditional adaptation was occurring, as revealed by the consistent presence of aftereffects. Aftereffects were still present on Day 3, despite the fact that adjustment to the prism was nearly immediate. The aftereffects were revealed by path lengths that were significantly greater than CG reaches before exposure to the prism. To establish this occurrence, we first tested the spatial efficiency of unperturbed reaches. Using a one-tailed grouped t test and the combined normalized path lengths of the first CG blocks from all three days, we tested the difference of normalized path lengths from 1. The result was significant, $p < .001$, $t(146) = 13.0$, and the mean was 1.06. We used this value to test the combined first trials on each day for CG viewing and then prism viewing. We used a one-tailed group t test to test the difference from 1.06. The result was that CG viewing was significantly different, $p < .001$, on all three days: Day 1, $t(17) = 6.5$; Day 2, $t(13) = 4.6$; Day 3, $t(11) = 4.1$; but prism viewing was only significantly different on Days 1, $t(17) = 4.0$, $p < .001$, and 2, $t(13) = 2.3$, $p < .03$, not on Day 3, $t(11) = -0.2$, $p > 4$. The relevant means for first trial normalized path lengths are previously listed. Next, we subtracted normalized path lengths for first trials of prism blocks from those of the first trials of the immediately following CG blocks. For each day, we tested the difference of these differences from 0 using a one-tailed grouped t test. The results were significant ($p < .05$ or better) on all three days: Day 1, $t(17) = 5.1$, $p < .001$; Day 2, $t(13) = 1.9$, $p < .05$; Day 3, $t(11) = 3.9$, $p < .005$. So, by Day 3, path lengths for prism trials became comparable to those of the unperturbed reaches at the beginning of each day. This did not occur for CG trials, in which path length remained longer on Day 3 than both unperturbed reaches and prism reaches. A residual aftereffect remained, showing that adaptation was still occurring, although the level of adaptation was significantly less than on Day 1.

[3] The participant's head was sometimes turned farther as the stylus was inserted into the target hole.

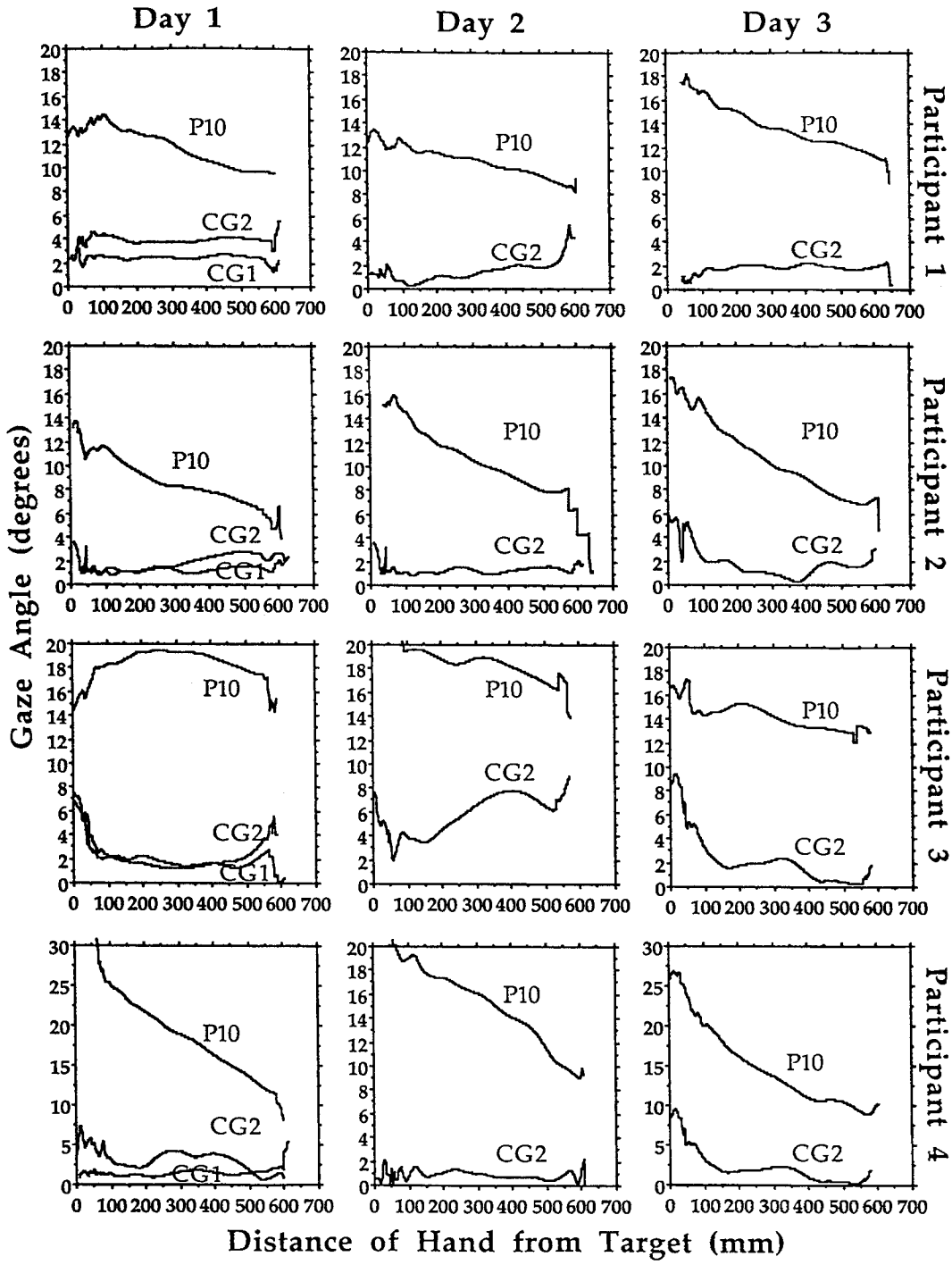

Figure 7. Mean gaze angle trajectories plotted in terms of the corresponding distance of the hand from the target. Plots for each of 4 participants on each of the 3 days. Each plot includes the mean trajectories for the first and second CG blocks and the first prism block. P10 = 10° prismatic displacement; CG = clear goggles condition.

General Discussion

Our participants performed targeted reaches with strong accuracy requirements, attempting to achieve movement times established in unperturbed conditions. We found that the times required to complete the reaches increased sharply when a 10° displacement prism was first applied to or removed from the performer's vision of the target. On average, as shown in Figures 1 and 4, movement times of about 1.04 s increased by about 600 ms when the prism was first applied and by 450 ms when it was subsequently removed. We also found that the movement times decreased over various time scales. First, movement times decreased gradually over a block of trials performed within a visual condition. However, the average initial rate of decrease from the first trial time remained constant over blocks and days at about 200 ms/trial. Second, the movement times for the first trial of each block decreased over blocks within a session. On average, these times dropped by about 100 ms per prism block and by about 70 ms per CG block. Third, first trial times decreased over days. On average, times for first prism trials dropped by about 200 ms per day. This is about 2 blocks worth of savings at the rate of 100 ms per block. Times for the first CG trials after the prism was removed dropped by about 140 ms per day, for 2 blocks worth of savings at the rate of about 70 ms per block.

Some of the drop in movement time across days reflects general improvement from practice in performing the reaching task, as shown by the drop in mean floor times for each day: Day 1 = 1.039 s; Day 2 = 0.971 s; Day 3 = 0.963 s.[4] The total drop of 76 ms represents about a fifth of the drop in first trial times for P10 and about a quarter of the drop for CG times.

These changes in movement times were all gradual and followed continuous trends. The trends were approximately exponential over trials within blocks and nearly linear for first trials over blocks. We sought further confirmation of continuous change in reaching behavior by analyzing the shapes and peak velocities of the trajectories. Hand trajectories were affected by both the application of the prism and its subsequent removal. Hand paths deviated from a direct path to the actual target location. The deviations produced increases in the distances traveled by the hand. As participants adjusted to the perturbations, the extent of the deviations decreased gradually. The pattern of results for path lengths was nearly identical to that for movement times except that path lengths increased more with removal of the prism at the beginning of CG blocks, whereas movement times increased more with application of the prism at the beginning of prism blocks. Analysis of peak velocities confirmed the implication that CG reaches were at higher velocities. The greater path lengths for CG reaches resulted because reaches to the left of the target were to locations farther from the launch platform. The launch platform was next to the participant's right hip.

Both movement times and path lengths revealed an aftereffect in the first trials of CG blocks. As shown in Figure 5, the effect decreased over days, but an effect remained present on the third day, showing that adaptation was occurring throughout the experiment.

Given the finding of improvements in the number of trials and time required to adjust to the prism, the key question was whether these improvements were produced by an increased rate of adaptation within blocks of trials. The clear answer was no. The rate of change in movement times over trials within blocks remained constant on all three days. Instead, the amounts by which the reaches were initially perturbed by the prism decreased gradually and nearly linearly over trials. These results suggest that there were two different processes of adjustment taking place at two different time scales. The first process of adjustment was traditional prism adaptation, which took place within blocks. The second process of adjustment was different and took place over blocks. What was the nature of this second type of change?

Welch (1978, 1986) suggested that if aftereffects accompany rapid adjustment, then adjustment might be explained in terms of *conditioned adaptation,* in which neutral stimuli become associated with adjustment to a prism so that the aftereffect becomes evoked as a conditioned response to the (no longer) neutral stimuli. For example, the goggle on which the prism was mounted might become associated with adjustment to the prism, evoking the aftereffect and producing some immediate adjustment on the first prism block of the second or third day. We had controlled for this possibility by using goggles in the nonexposure or CG condition as well. If merely donning the goggles had evoked the aftereffect, then we should have observed a perturbation and adjustment in the very first CG block on the second or third day. No such adjustment was observed, especially by the third day.

However, conditioned adaptation should be evoked only by conditions that are truly specific to the relevant prismatic displacement. For instance, a shearing of the optical pattern accompanies prismatic alteration of the direction from which light is projected to the eye (Held, 1980). Comparatively, the pattern near the base of the prism is stretched, while that near the apex is compressed. Because such optical transformations are both salient and invariably paired with particular prismatic displacements, they would be the most effective discriminative stimuli for conditioned adaptations.

As already mentioned, Welch et al. (1993) also studied changes in adaptation with repeated exposure to a prism, but they used pointing error as the measure (see also Bridgeman, Anand, Browman, & Welch, 1992; Welch, Bridgeman, Anand, & Browman, 1991). Welch et al. (1993) found a drop in error for the first trials of successive prism blocks. However, they also found that a residual aftereffect remained at the end of a no-prism condition even after participants had fully adjusted, performing without significant error. Welch et al. tested the possibility that the drop in first trial errors was produced by the residual aftereffect. They performed another experiment in which exposure was alternated between a leftward versus a rightward prismatic

[4] These times were estimated using the exponential model, as shown in Figure 6.

displacement. The expectation was that the symmetrical displacements would annihilate any residual aftereffect. This expectation was confirmed, but the previous result was also confirmed; that is, progressively more rapid adjustment due to smaller errors on the initial trial in a block. Welch et al. concluded that an aftereffect could not account for the decreases in pointing error. What could? They concluded that it was conditioned adaptation. The problem with this account is that they also found in their second experiment that rapid adjustment generalized to another stronger prism. This circumstance implies the availability and use of information about the actual direction of a target.

What might provide such information? One possibility is the shearing of the optical pattern. The presence of the shearing indicates the presence of the prism. Given the single 10° displacement in our experiment, participants may have been learning to use this information implicitly to calibrate their reaches. This information (i.e., the mere presence of the shearing) would not generalize fully to another prism of different magnitude. Indeed, in our experiment, the ability to adjust rapidly did not fully generalize to performance with a larger 15° prism. In contrast, the direction and amount of shear of the optical pattern could provide information about the direction and degree of displacement. Participants in Welch et al.'s second experiment may have learned to detect this additional information, which would generalize to prisms of different magnitudes. Reversal of the direction of the prism during acquisition might have led those participants to discriminate and to become sensitive to the degree of the change in optical pattern. The fact that rapid adjustment did generalize implies that the participants did learn to use this information to calibrate their reaching.

In our experiment, there was another possible source of information, because participants were allowed to move their heads. In fact, participants naturally tended to move their heads forward as they reached. Held and Freedman (1963) described information about the perturbation in optical direction that would be produced by displacements of the eye. Translation of the point of observation in a structured surround yields optical flow radially outward from a fixed point that corresponds to the locus in the surround toward which the observer is moving. Studies on the perception of heading from optic flow have shown that heading estimates accurate to within 1°–2° can be made on the basis of simulated flow (Warren, 1976; Warren, 1990; Warren & Hannon, 1990; Warren, Mestre, Blackwell, & Morris, 1991; Warren, Morris, & Kalish, 1988). The optical node continues to correspond to the locus of heading despite prismatic alteration of the direction of the node relative to the point of observation. Although the prism perturbs the optical direction, it does not destroy the spatial–temporal optical pattern that specifies the direction of travel of a moving observer (Zhang & Bingham, 1993).[5] For instance, if the goal was to guide the eye to some locus, this could be achieved while viewing through a prism by moving, so as to keep the node of radial outflow at the point in the optical pattern corresponding to the targeted locus. The same strategy can be used to guide the hand to a target, but the flow would be radially inward as the image of the hand shrinks with movement of the hand away from the eye. With the application of a prism, a discordance arises between the optical direction and the optical consequences of moving in that direction, and observers have to learn to use the optical flow dissociated from optical direction. The information is not purely optical, of course, because information about self-motion from kinesthesis and/or motor control would also be required. If participants had learned to use this information in our experiment, then their performance should have generalized fully to the 15° prism. It did not.

Whatever information observers were using, it was clear that they acquired a new skill that they developed by extending an old skill. At the end of the experiment, participants were adjusting rapidly to the prism and were reaching successfully in a new and different way. For instance, accurate targeted reaching involves head movement used to center the target in the visual field (Carnahan, 1992) but normally the head is pointed at the target. Our participants were pointing their head at an angle to the target while reaching to the actual location of the target; that is, they reached in one direction and pointed their head in another. We infer that they did this to foveate visual information about the target. Redding and Wallace (1985, 1988) also noted that their participants typically held their heads at an angle relative to the direction of heading when asked to walk while wearing prisms. In that case, observers seem to have centered the expansion pattern in the visual field.

Beyond the head movement, of what might the new skill consist and what did its acquisition involve? Three possible components are (a) rapid on-line visual guidance, (b) detection of information allowing visual perception of actual target direction, and (c) traditional adaptation. It is unlikely that speeded on-line guidance would be gradually acquired anew within each block of trials. Rather, improvement in on-line guidance is likely to have occurred over blocks of trials and over days, as revealed by the progressive drop in the floor or minimum mean movement time reached at the end of each block of trials and as exhibited in the CG trials at the beginning of each day before participants experienced the prism. This drop in the floor accounted for about one fifth of the improvement in first prism trial movement times. The repeated need to guide the stylus into the hole as rapidly as possible while viewing the target through the prism is likely to have generated improvements in on-line visual guidance. At the very least, participants might have been expected to be more vigilant about on-line guidance, as suggested by Jakobson and Goodale (1989).

Prism adaptation, as traditionally measured using aftereffects, was clearly involved in the acquisition of the skill, but it was involved less and less in the increasingly rapid adjustments. This was shown by decreasing amounts of

[5] Zhang and Bingham (1993) found a single type of head movement that, in certain conditions, would annihilate the radial outflow topology, but that movement and those conditions were exceptional and did not occur in the current experiment.

aftereffect, although the amounts remained statistically significant even at the end. The precise role of traditional adaptation in the acquisition of rapid adjustment to prisms remains to be determined. Redding and Wallace (1997a) extended their previous analyses at some length to incorporate the current results (Bingham & Romack, 1992; Bingham, Romack, & Stassen, 1993a, 1993b; Romack, Buss, & Bingham, 1992), in addition to those of Welch et al. (1993). In so doing, Redding and Wallace suggested that traditional adaptation and the acquisition of what they call *contingent adaptation,* or a *context-specific side pointing strategy,* may interfere with one another. The reason is that traditional adaptation requires detection of misalignment, and successful side pointing in contingent adaptation would eliminate this detection. We did find that aftereffects diminished as adjustment became more rapid. Redding and Wallace also view traditional adaptation (with aftereffect) as the more functionally effective and desirable end state, suggesting that it should generalize better than contingent adaptation. However, the Welch et al. results would seem to undermine this idea, because they found rapid adjustment to generalize quite well to a prism of twice the power of that experienced by participants during training. As we have pointed out, this ability to generalize the rapid adjustment entails the detection and use of information specifying the actual location of a target despite prismatic displacement of the visual direction. The implication is that contingent adaptation must, in fact, be perceptual learning; that is, participants must become sensitive to forms of information that they previously had not been able to detect and to use.

Accounts of traditional adaptation essentially hypothesize that reaching as a measure is used during the exposure period to recalibrate a relation between visual direction and proprioception of the arm. The proprioception is used, in turn, to control the direction of a reach performed without visual guidance (see Bedford, 1993a, 1993b, for a recent account of adaptation in terms of types of mappings between dimensions). On the basis of our results and those of Welch et al. (1993) that show acquisition of rapid adjustment, as well as our result showing that the rate of adaptation remains constant, we have hypothesized that reaching is used as a measure to discriminate and to calibrate new sources of visual information. Examples of possible sources of information are the presence or the direction and degree of optical shear or the dissociation of the focus of expansion in optical flow from the visual direction. Once these become salient, they could be used to detect a perturbation to the visual direction and rapidly recalibrate optical information about direction.

Such perceptual learning would be the more functionally effective way of dealing with prismatic perturbations of visuomotor behaviors. We have found that the rate of adaptation does not change over repeated practice and, accordingly, adaptation cannot be viewed as functionally adaptive in the long run. The skill acquired by participants who are able to adjust immediately is much more adaptive, as the examples of spear fishing or daily use of corrective lenses make obvious. In the short term, the traditional process of adaptation appears to be a useful step along the way to a more rapid and flexible facility.

Finally, we should note that Pick, Rieser, Wagner, and Garing (1999) have recently found a similar combination of adaptation and perceptual learning in the recalibration of rotational locomotion. Participants had to turn through an arc on a turntable to orient toward a target after an exposure condition in which they experienced discrepant optical and biomechanical turning speeds. Akin to this study, the finding was that sensory adaptation was not as functionally effective as the perceptual learning.

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