Generalization of Prism Adaptation

Gordon M. Redding
Illinois State University
Normal, IL 61790-4620

And

Benjamin Wallace
Cleveland State University
Cleveland, OH 44115
USA

Contact Information:
Gordon M. Redding, Professor Emeritus
Illinois State University
Department of Psychology
Campus Box 4620
Normal, IL 61790-4620
USA
gredding@ilstu.edu

Abstract

Prism exposure produces two kinds of adaptive response. Recalibration is ordinary strategic remapping of spatially coded movement commands to rapidly reduce performance error. Realignment is the extraordinary process of transforming spatial maps to bring the origins of coordinate systems into correspondence. Realignment occurs when spatial discordance signals non-correspondence between spatial maps. In Experiment 1, generalization of recalibration aftereffects from prism exposure to post-exposure depended upon the similarity of target pointing limb postures. Realignment aftereffects generalized to the spatial maps involved in exposure. In Experiment 2, the two kinds of aftereffects were measured for three test positions, one of which was the exposure training position. Recalibration aftereffects generalized non-linearly, while realignment aftereffects generalized linearly, replicating Bedford (1989, 1993a) using a more familiar prism adaptation paradigm. Recalibration and realignment require methods for distinguishing their relative contribution to prism adaptation.

Key words: cognitive learning, coordination, motor control, perceptual learning, recalibration, realignment, spatial mapping

---

1 This manuscript is currently in press (2006) in the Journal of Experimental Psychology: Human Perception and Performance. Copyright is held by the American Psychological Association. A partial report of these data was presented at the 45th Annual Meeting of the Psychonomic Society, Minneapolis, MN, 6-9 of November 2004. The general form of the second experiment was suggested by discussions with Yves Rossetti and by Felice Bedford’s persistent call for multiple test targets in prism adaptation. Correspondence should be addressed to Gordon M. Redding, Professor Emeritus, Illinois State University, Department of Psychology, Campus Box 4620, Normal, Illinois, 61790-4620, USA. Electronic mail may be sent via the Internet to gredding@ilstu.edu.
Generalization of Prism Adaptation

Prism adaptation is commonly studied by having a person put on goggles bearing wedge prisms that laterally displace the visual field, for example, in the rightward direction. The person then interacts with the environment, for example, by pointing toward visual targets. Initially, the person makes pointing errors to the right of a target, but errors disappear in a dozen or so pointing trials, depending upon exposure conditions. The person has adapted to the prismatic displacement. In the hundred years since its discovery (Helmholtz, 1909/1962) a primary question has been how such adaptation occurs: what are the adaptive processes involved in prism adaptation?

There seems to be general agreement that prism adaptation involves some kind of spatial remapping, for example, between eyes and hand, but there agreement ends! Historically, two classes of competing explanations can be identified, variously called, respectively, “motor learning” vs. “perceptual learning” (Cunningham & Welch, 1994; Beckett, 1980; Welch, 1978), “central processing” vs. “peripheral processing” (Finke, 1979; Hardt, Held, & Steinbach, 1971), “cognitive correction” vs. “true adaptation” (Weiner, Hallett, & Funkenstein, 1983), “cognitive learning” vs. “perceptual learning” (Bedford, 1989, 1993a, 1999), “skill acquisition” vs. “recalibration” (Clower & Boussaoud, 2000; Welch & Sampanes, 2004), and “recalibration” vs. “realignment” (Redding & Wallace, 1997a, 2002).

The contrasting terms used for the competing explanations suggest the following summary: The first candidate for prism adaptation involves higher level strategic remapping controlled by the cognitive system and is the ordinary response to performance error produced by prismatic displacement, a kind of cognitive learning. The second candidate involves lower level spatial remapping constrained by the structure of the perceptual system and is the response to mismatch between spatial maps produced by prismatic displacement, a kind of perceptual learning. We have synthesized these competing explanations to form a general theory of adaptive perceptual-motor performance (Redding & Wallace, 1997a, 2002; for recent reviews, see Redding, Rossetti, & Wallace, 2005, Redding & Wallace, in press). As commonly executed, the prism adaptation procedure evokes all of the adaptive capacity of the perceptual-motor system. Therefore, we have found analysis by adaptive components to be a productive approach to prism adaptation.

The initial response to prismatic displacement is ordinary strategic (cognitive) remapping of the spatially coded movement commands, for example, from visual eye-head to proprioceptive hand-head sensory motor systems to quickly reduce performance error. We call this first response recalibration, an instance of cognitive learning. For example, a person may use error information from a previous target pointing trial to select a virtual target position for execution of the next trial (side pointing) such that performance error is reduced (Redding & Wallace, 1993; Rossetti, Koga, & Mano, 1993). Traditionally, rapid error correction in prism adaptation has been recognized as “conscious correction” (Welch, 1978), but this term depreciates the complexity and pre-conscious partially automatic nature of motor control (Redding & Wallace, 1993, 1997a).
Recalibration not only involves resetting the feedforward movement plan\(^1\) with offline knowledge of results, as in the above side-pointing example, but also the strategic use of available online visual feedback to reduce performance error (e.g., a strategy of zeroing in on a target). Further, recalibration involves adjustments in the size and position the areas of visual and proprioceptive space dedicated to the task (i.e., the regional task-work space, including positions of targets and obstacles to movement; Redding & Wallace, 2002, in press). The skilled actor has available a repertoire of strategies to maximize performance.

The second response to prism exposure is an automatic (perceptual) remapping of local spatial maps (e.g., for eyes and/or limb) onto all other spatial maps\(^2\) (Redding & Wallace, 1997a, 2002). For example, rightward prismatic displacement shifts the head-centered origin of the visual coordinate system rightward: consequently, the normal lateral separation from the (likely) shoulder-centered origin for the limb coordinate system is reduced. The normal transformation of visually coded targets into limb coordinates must be adjusted to restore veridical spatial mapping. We call this second response realignment, an instance of perceptual learning.

Transformation adjustment (realignment) is “peripheral” in the sense that each spatial map (e.g., for eye-head and hand-head systems) has its own unique transformation that maps its coordinates onto all other spatial maps. Realignment is localized, for example, for the visual or proprioceptive coordinate systems, depending upon exposure conditions. Local realignment is additive: that is, the sum of visual and proprioceptive realignment equals the total realignment occurring in, for example, the eye-hand coordination loop exercised during exposure. There is nothing left over that might be “central”. The evidence for local and additive realignment is overwhelming and far too extensive to be repeated here (for recent reviews, see Redding & Wallace, 1997a, 2000, in press, and Redding et al. 2005).

In contrast to recalibration, which directly reduces the performance error produced by prismatic displacement, realignment reduces spatial discordance, the non-correspondence of spatial maps, and indirectly reduces performance error. Detection of misalignment occurs when the position expected from a feedforward movement command coded, for example, in visual coordinates is different from the achieved position coded, for example, in proprioceptive limb coordinates (Redding & Wallace, 1996, 1997a, 1997b). The expected-achieved difference constitutes spatial discordance and signals a gradual adjustment in the parameters of the transformation that, in the case described, maps proprioceptive limb coordinates onto all other spatial maps.

---

\(^1\)A feedforward movement plan involves a predicted movement sequence such that deviations can be anticipated and quickly corrected before they can occur or at least before they can become large (Redding & Wallace, 1997a). For example, inertial differences between limb segments can be predicted and accounted for in the movement plan; slippage of the grip on a cup handle can be similarly anticipated. Thus, feedforward control is not limited by the relatively slow response time of feedback control (for a review, see Desmurget & Grafton, 2003).

\(^2\)We believe that the various spatial maps are linked through a noetic nexus, a switching-point that routes spatial information from the various sensory-motor systems through a common spatial reference frame. Common reference, however, lies in the operation of the collection of transformations, not necessarily in a topographically identifiable neural map. (For further discussion, see Redding, Rossetti, & Wallace, 2005).
Slowly developing realignment invisibly adds to recalibration and may even produce additional performance error (Redding & Wallace, 1993, 2001). Realignment is hidden from recalibration processing, and alignment transformations do not have to be computed by calibration processes. At the level of recalibration the state of alignment is not accessible. In everyday perceptual-motor performance, where strategic recalibration is extensively deployed, alignment spatial mapping is a completely automatic process. Only when misalignment (arising from experimental manipulation, growth, or pathology) occurs does the realignment process become apparent.

While substantial, the evidence for involvement of both adaptive processes in the common prism adaptation procedure has been largely indirect (for reviews, see Redding, Rossetti, & Wallace, 2005; Redding & Wallace, in press). For example, failures of visual and proprioceptive realignment aftereffects measured separately to additively match joint measures of visual-proprioceptive realignment aftereffects have been traced to transfer of contaminating recalibration (e.g., Redding & Wallace, 1978, 1988b; Wallace & Redding, 1979; Welch, Choe, & Heinrich, 1974). Overcompensation for the prismatic displacement during exposure has been traced to joint and conflicting contributions of recalibration and realignment (e.g., Redding & Wallace, 1993, 2000). The finding that sight of the limb in the starting position (visual calibration) produces more precise (variable error), but less accurate (constant error) pointing during prism exposure compared to the limb not being visible in the starting position (proprioceptive calibration) has been attributed to the hidden, automatic nature of realignment (Redding & Wallace, 2001).

The present experiments were designed to directly compare the separately measured relative contributions of recalibration and realignment. These experiments were based on Bedford’s (1989, 1993a) finding that cognitive and perceptual learning (recalibration and realignment, respectively) exhibit different kinds of generalization.

Bedford (1989) used an abstracted version of the prism adaptation procedure in which only a target and the finger pointing toward the target were visible through laterally displacing prisms. Therefore, discrete pairing of positions in visual and proprioceptive coordinate systems could be selected for training, in contrast to the usual prism exposure procedure in which a new limb position is mapped for each single visual position. The procedure, therefore, enabled measurement of generalization from training (exposure) with discrete visual-proprioceptive pairs to testing (post-exposure) with other discrete, untrained visual-proprioceptive pairs. Bedford found that training with a single visual-proprioceptive pair generalized globally to untrained pairings: a zero slope linear function. Moreover, training with two or three pairs showed a linear

---

1 We have previously used the term “transparent” to refer to the knowledge relationship of calibration to alignment: calibration does not “see” the present state of alignment, at the level of calibration the state of alignment is not “known”.

2 Realignment is automatic only in so far as recalibration processes enable spatial discordance detection. For example, to the extent that a side pointing strategy is deployed, the limb achieves the commanded position, spatial discordance is not detected, and alignment does not occur. Recalibration and realignment interact, not always in mutually supportive ways (Redding & Wallace, 1993, 1996, 1997b).

3 The calibration-alignment processing distinction may also correspond to localization of function in cerebrum and cerebellum, respectively (Jeannerod & Rossetti, 1993). The ability to adapt to prismatic displacement remains with intact cerebellum but damaged posterior parietal cortex (Pisella, Michel, Gréa, Tilikete, Vighetto, & Rossetti, 2004), while prism adaptation is lost with damaged cerebellum, but intact posterior parietal cortex (Baizer, Kralj-Hans, & Glickstein, 1999; Martin, Keating, Goodkin, Bastian, & Thach, 1996a; Weiner et al 1983).
transfer function approximated by the training set. Guigon and Baraduc (2002) have shown by artificial neural net simulation how the nervous system might achieve such transformational mapping.

Bedford (1993a) further found that when a spatial mapping task is presented to subjects as a cognitive learning task generalization to untrained pairs displayed the traditional associative generalization gradient: the greater the separation between a trained pair and an untrained pair, the less generalization. In this procedure no prismatic displacement was present and the visual-proprioceptive pairings were simulated by computer program. Therefore, in contrast to the prism exposure task, there was never a discrepancy (spatial discordance) between seen and felt positions of the limb.

Bedford (1993b, 1999) proposed that “true” prism adaptation falls in the class of perceptual learning, which is subject to endogenous constraints, constraints that reflect locally Euclidian spatial regularities embodied by evolution: in this case, the regularity that Euclidian space is uniform regardless of how it is represented. In contrast, cognitive learning is unconstrained and, in principle, can accommodate any arbitrary spatial mapping. Moreover, cognitive learning is associative in nature, showing generalization gradients along dimensions of similarity between training and test.

Despite Bedford’s distinction between context-independent and context-dependent adaptation, perceptual learning and cognitive learning, respectively, and despite the substantial evidence for two adaptive processes in ordinary prism exposure (Redding & Wallace, 1988b, 1993, 2001, 2002, 2003a) the distinction has not been widely recognized. Investigations using common, non-reduced prism adaptation procedures continue to find generalization specific to the conditions of exposure (i.e., evidence of cognitive learning). And, investigators indiscriminately call these findings “prism adaptation”.

For example, Martin, Keating, Goodkin, Bastian, and Thach (1996b) found that adaptation during ball throwing did not generalize from overhand to underhand throws. Similarly, Field, Shipley, and Cunningham (1999) found that adaptation to ball catching did not generalize to different catching movements. Fernández-Ruiz, Hall-Haro, Díaz, Mischner, Vergara, and Lopez-Garcia (2000) found that adaptation during ball throwing did not generalize well when limb weighting was different from exposure to post-exposure. Kitazawa, Kimura, and Uka (1997) found that adaptation with fast movements did not generalize to slow movements and vice-versa: moreover, the amount of generalization depended upon the similarity in movement speed. Baraduc and Wolpert (2002) found that generalization of adaptation was specific to the starting posture of the pointing limb during prism exposure.

Is cognitive learning (recalibration) the only or dominant process in the common prism adaptation procedure? Can perceptual learning (realignment) only be demonstrated with Bedford’s reduced procedure? We believe that the answer is “no” to both questions (Redding & Wallace, 2001, 2002). The present experiments tested this hypothesis by directly comparing the differential generalization of realignment and recalibration using the common, non-reduced prism adaptation procedure.

In the first experiment recalibration generalization was examined as a function of similarity between exposure and post-exposure tasks. Realignment generalization was measured by using post-exposure tests that were dissimilar from the exposure task, but which measured the same spatial maps involved in exposure. The second experiment was designed to obtain generalization gradients by employing multiple post-exposure tests targets in a task that was
otherwise similar to the exposure task (recalibration) and in a task that was dissimilar from the exposure task, but which measured the spatial maps involved in exposure (realignment).

Experiment 1

The first experiment was designed to identify the different, separable contributions of recalibration and realignment to prism adaptation. To assess recalibration, post-exposure tests were created that were either identical to or specifically different from the exposure task. To assess realignment, post-exposure tests measured both the visual eye-head and proprioceptive hand-head spatial maps evoked during exposure, tested separately and together, but which were otherwise largely dissimilar from the exposure task.

Table 1 illustrates the logic of the experimental procedure. The first three and last three experimental events (E1, E2, E3, E9, E10, E11) were tests of visual, proprioceptive, and visual-proprioceptive straight ahead: visual shift (VS), proprioceptive shift (PS), and total shift (TS). These tests measured each of the spatial maps involved in exposure and the coordination of the two spatial maps, but they were otherwise largely different from the exposure task (e.g., in limb posture, starting position, and mode of response) and not expected to be influenced by recalibration. Differences between these pretests and posttests provided measures of spatial realignment.

Table 1
Illustration of the Experimental Procedure for Experiment 1.

<table>
<thead>
<tr>
<th>Realignment Pretests</th>
<th>Recalibration Pretests</th>
<th>Prism Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Feedback</td>
<td></td>
<td>Feedback</td>
</tr>
<tr>
<td>VS</td>
<td>E2</td>
<td>E3</td>
</tr>
</tbody>
</table>

Note: E: (Event) Ordinal position of experimental events. VS: (Visual Shift) Non-manual adjustment to visual straight-ahead. PS: (Proprioceptive Shift) Manual pointing to straight-ahead without vision. TS: (Total Shift) Manual pointing to visible straight-ahead target without feedback. Order of these three realignment tests was random. DTP: (Distal Target Pointing) Manual pointing to visible straight-ahead target from distal starting position. PTP: (Proximal Target Pointing) Manual pointing to visible straight-ahead target from proximal starting position. Order of DTP and PTP recalibration tests was counterbalanced and feedback was provided only during exposure.

The exposure task (E6) was target pointing under prismatic displacement, with starting position either near the body (proximal target pointing, PTP) or removed from the body (distal target pointing, DTP). The two conditions differed not only in starting position and limb posture, but also in movement speed because movement time was the same, but movement distance was different. Visual feedback was restricted to sight of the finger at the end of the pointing movement (i.e., terminal feedback). Consequently, realignment was expected to be largely restricted to the visual eye-head sensory-motor system (e.g., Redding & Wallace, 1990, 1993, 2000; Uhlarik & Canon, 1971).
Immediately before and after exposure, but after and before the realignment tests, two pretest and posttest generalization measures of recalibration were obtained (E4, E5, E7, E8), one of which was identical to the exposure task, except for the absence of performance feedback and prismatic displacement. The other differed in starting position and consequently in limb posture and movement speed. These tests involved coordination of the visual and proprioceptive spatial maps and, consequently, also measured spatial realignment. However, these two tests further provided a measure of associative generalization. Assuming a constant contribution of realignment, the differential generalization between the test identical to and the test dissimilar from exposure conditions constituted an independent measure of differential strategic recalibration.

Similarity between exposure and post-exposure conditions was expected to affect generalization of recalibration, but not generalization of realignment, which was expected to occur because the exposure spatial maps were involved in posttest, regardless of dissimilarity between exposure and post-exposure conditions. More specifically, generalization of recalibration was expected to be greater when exposure and test conditions matched, but generalization of realignment was expected not to be different for the different exposure conditions.

Method

Participants. The 32 subjects were right-handed student volunteers at Cleveland State University. All subjects had self-reported normal vision or vision was corrected to normal by contact lenses. These subjects were treated in accordance with the “Ethical Principles of Psychologists and Code of Conduct” (American Psychological Association, 1992).

Apparatus. The apparatus is illustrated in Figure 1. This structure consisted of a two-layer, rectangular, wooden, box-like frame (24 cm high, 105 cm wide, and 74 cm deep) placed on a table and open on the side facing the subject. All visible surfaces were homogeneously white. Attached to the front of the apparatus was a Marietta Apparatus Co. (Marietta, OH) Model No. 75-A-2-12 chinrest. Subjects sat at the apparatus, with head position constrained, and made sagittal pointing movements toward a target located on the back vertical surface of the apparatus.

![Figure 1. Apparatus. Subjects were seated, with head constrained by a chinrest, and wearing goggles holding the prisms. For realignment pretests and posttests, the subject’s right arm was not visible on the lower level of the apparatus, target lines were introduced on the back vertical surface and starting position for sagittal pointing was the base of the chinrest. For recalibration pretests and posttests, subjects placed their arm on the top level and the shelf was positioned to prevent any sight of the pointing limb. For exposure, subjects placed their arm on the top level and the shelf was positioned to afford view of only the tip of the pointing finger at the terminus of the movement (Experiment 1 and 2) or after leaving the starting position the finger was visible over the entire movement path (Experiment 2). The removable box established a distal starting position for target pointing, halfway to the target.](image-url)
When subjects placed their arm within the structure, on the lower layer, the arm was not visible. In this area, during realignment tests before and after prism exposure, limb position was measured by determining its position along a calibrated 180 deg. arc. The origin of the measurement scale was below the subject’s chin, near the trunk. Thus, limb position was measured as the angle made by the hand relative to the body midline. Starting position for sagittal pointing during realignment tests before and after prism exposure was the base of the chinrest.

During prism exposure and recalibration tests, subjects placed their arm upon the upper layer. A second measurement scale for recording performance was positioned on the surface of this upper layer and not visible to the subject. An occluding shelf was placed 15 cm above the upper layer of the apparatus, approximately just below the subject’s nose. The in-depth width of this shelf was adjusted for individual subjects such that the limb was not visible for recalibration tests and only the first joint of the subject’s finger was visible for prism exposure when the arm was fully extended toward a target. Two starting positions for sagittal pointing during exposure and recalibration testing were specified by the vertical support of the chinrest and by the distal side of a removable box positioned against the vertical support of chinrest, filling half of the distance to the back surface of the apparatus (see Figure 1). Thus, starting position was proximal, near the body, or distal, about halfway to the target.

Limb postures for pointing on upper and lower level of the apparatus were different. On the upper level with the limb movement was more constrained, restricted to a plane near horizontal with the shoulder. In contrast, on the lower level pointing movements were less constrained, being made in the region below shoulder level.

Subjects wore welder's goggles with a Risley prism mounted in each eyepiece that could be set to produce lateral prismatic displacement (right or left) of the optic array varying from 0 to 30 diopters (1 diopter = .57 arc deg.) and which afforded binocular vision. Each circular eyepiece subtended a visual angle of approximately 30 deg. and the width of the binocular field was approximately 45 deg.

Design. A mixed design was employed with Exposure Starting Position (proximal or distal) and Order of Starting Position for Recalibration pre-post tests (distal-then-proximal or proximal-then-distal) as the between-subject factors and Exposure Trials as the within-subjects factor. Subjects were randomly assigned to the four groups formed by factorial combination of the two between-subject factors. Measures of terminal limb position in sagittal pointing were recorded for each of 30 exposure trials.

Before exposure to one of the between-subject conditions and after the exposure period, subjects performed three realignment tests, without prismatic displacement and without visual feedback or knowledge of results. These tests were designed to provide aftereffect measures of realignment of perceived visual position with perceived limb position (Visual Shift), realignment of limb position with visual position (Proprioceptive Shift), and the total realignment between eye and limb (Total Shift). The order of these alignment tests was random, both before and after prism exposure.

Immediately before exposure (after the realignment pretests) subjects performed two pre-exposure recalibration baseline target-pointing tasks. Immediately after exposure (before the realignment posttests) subjects performed the same two tasks as post-exposure recalibration measures. The two tasks were identical except that starting position was either distal or proximal and there was no prismatic displacement, visual feedback or knowledge of results. Order of distal
and proximal starting positions was counterbalanced, with the same order used before and after exposure for a given subject.

The post-tests for recalibration were always performed first, before the realignment post-tests, to maximize the similarity with exposure. If subjects had experienced the realignment tests first the discontinuity between exposure and recalibration tests would likely have annulled recalibration strategies deployed during exposure. As will be seen, levels of realignment were comparable to those usually found and such adaptation did not suffer from the delay in testing.

**Procedure.** Upon arrival in the laboratory, each subject received a brief description of their participation, including the fact that perceptual-motor coordination tests would be given before and after a short period of eye-hand coordination activity while looking through prisms. Subjects were not informed of the nature of the distortion: only that the prisms might affect their performance and that they should try to perform the task as accurately as possible. The subject was seated in a chair before the apparatus with head positioned in the chinrest and wearing the prism bearing goggles. The subject was then asked to perform each of the pre-exposure realignment tests.

The visual shift test involved no limb movement. Instead, the experimenter introduced a moving, visible, vertical target line (.2 by 8 cm) on the back vertical surface of the upper layer of the apparatus and at the subject’s eye level. When the experimenter moved this target laterally across the subject's visual field, the subject verbally indicated when the target appeared to be straight ahead of the nose. Ten trials were given. Five trials started with the target randomly placed in the right half of the visual field and five trials started randomly in the left visual field. Order of left and right starting positions was also random. The subject’s eyes were closed when the line was moved to a starting position. The duration of a test trial varied approximately between 5 and 10 s, depending upon the distance from the random starting position to the position that a subject judged to be straight-ahead of the nose. The prisms were set to zero diopters for this test, as was true for all pre-post exposure test situations. Because this test was referenced to the head, difference between this baseline pre-exposure measure and performance on the same test administered after prism exposure can be assumed to provide an aftereffect measure of realignment in the visual (eye-head) system.

The proprioceptive shift test required the subjects to place their right hand on the lower layer of the test apparatus, against the base of the chinrest, and point sagittally to the position in space believed to be straight ahead of their nose. This task was performed with vision occluded by a blindfold placed over the prism-bearing goggles. The test was performed 10 times at a rate of 1.5 s for each out and back segment of the pointing movement. Because this test was referenced to the head, change in performance after prism exposure can be assumed to provide an aftereffect measure of realignment in the proprioceptive (hand-head) system.

---

1 The term “visual shift” is used to designate adaptive change in the eye-head system that has phenomenal consequences for visual perception. The basic nature of such change may be realignment of either retinal local sign or direction of gaze (e.g., Crawshaw & Craske, 1974; Harris, 1980). Current theory development does not permit a comparison between these two possible accounts of visual change (but see Redding & Wallace, 1997a), and the aftereffect test for visual shift used in the present experiment was sensitive to either or both kinds of change.

2 The term “proprioceptive” is used to designate any adaptive change in position sense at joints between head and hand or even fingers. We assume that the hand-head system is hierarchically organized (Redding & Wallace, 1992, 1993, 1997a, 2002; see also Jeannerod, 1988) such that any proximal change extends to positioning of more distal joints. The present proprioceptive shift test was designed to detect all position sense changes in the hand-head system. Indeed, we think of the spatial map for the limb as being defined by the combination of joint
The total shift test was similar to the proprioceptive shift test, except that the subject was not blindfolded, but pointed toward a visible, vertical target line (.2 by 8 cm) located physically straight-ahead at eye level on the back vertical surface of the upper layer of the apparatus. During this test, the subject viewed the target with no prismatic displacement and accuracy of pointing was not known to the subject because the hand was on the lower level of the apparatus and not visible. Ten measures were taken with each out and back movement segment requiring 1.5 s. Because this test involved the complete eye-hand coordination loop, difference between this baseline pre-exposure measure and performance on the same test administered after prism exposure can be assumed to provide an aftereffect measure of realignment in either or both the visual (eye-head) and proprioceptive (hand-head) systems.

Following the realignment baseline tests, subjects performed two pre-exposure recalibration baseline tests in counterbalanced order. Both of these tests required pointing, with the prisms set to zero diopters, toward a visible, vertical target line (.2 by 8 cm) located physically straight-ahead at eye level on the back vertical surface of the upper layer of the apparatus. For these tests the subject’s limb was located on the upper level of the apparatus as it would be during the following prism exposure. During these tests, the subject viewed the target with no prismatic displacement and accuracy of pointing was not known because view of the limb was occluded. Ten measures were taken for each test with each out and back movement segment requiring 1.5 s.

The difference between the recalibration tests was in the starting position for pointing, distal or proximal. The recalibration pre-post tests were also similar or dissimilar to exposure in movement speed because movement time was constant, but movement distance was different. The difference in performance on these two pre-exposure measures and the same tests performed immediately after exposure (before realignment tests) provided measures of recalibration under specific similar or dissimilar conditions: when starting position was the same as or different from starting position during exposure. Note that the proximal starting position for recalibration tests and for realignment tests was quite different, being performed on different layers of the apparatus and requiring different limb postures.

Following establishment of the realignment and recalibration baselines the prisms were set to displace the visual field 20 diopters (11.4 deg) in the rightward direction and subjects were randomly assigned to one of the two exposure starting-position groups. For the proximal starting position condition the subject’s right hand was positioned on the upper level of the apparatus against the vertical upright of the chin rest, near the body trunk. For the distal starting position the subject’s right hand was positioned on the upper level of the apparatus 37 cm in front of their body trunk, against the distal surface of the box (see Figure 1). The subject’s limb was not visible in either starting position. The displaced visual field contained a vertical target line (.2 by 8 cm) located physically straight-ahead at eye level on the back vertical surface of the upper layer of the apparatus, but was optically displaced 11.4 deg. to the right. Subjects attempted sagittal pointing movements toward the visible, vertical target line.

In both exposure conditions sight of the pointing limb was limited to the first joint of the pointing finger by the adjustable occluding-shelf. Thus, visual feedback was delayed until near the terminus of the pointing movement; that is, terminal feedback. The exposure arrangements for the two exposure conditions viewed from above the apparatus are schematically illustrated in Figure 2. The limit of the occluding shelf varied, depending upon the subject’s arm length, and
the illustrated arrangement assumes an average arm length of 50 cm. Note that target was, on average, 24 cm beyond the subjects’ reach.

Figure 2. Exposure Arrangement. Exposure conditions are illustrated in a top-down schematic view, showing the straight-line movement paths from the two starting positions (distal or proximal) toward the target: starting position was not visible for either condition. The limit of the occluding shelf varied, depending upon the subject’s maximal reach, to produce terminal visual feedback. The illustration assumes an average reach of 50 cm. (Experiment 1)

Upon completion of an outward pointing movement, subjects immediately reversed direction, returned to the starting position, then pointed again toward the target, and so on with continuous out-and-back movement. Each segment (out or back) of movement required approximately 1.5 s. In this manner, subjects pointed 30 times toward the target. Because movement distance was shorter from the distal starting position movement speed was slower compared to the proximal starting position.

For all groups, terminal accuracy in pointing at the target was visually observed and recorded by the Experimenter for each subject on each trial. These observations were made when the subject’s finger paused briefly, signaling primary movement completion. Movements after a pause but not in the opposite (return) direction were considered secondary corrections. Such secondary movements were discouraged and, in fact, appeared only infrequently. Of course, visual information about terminal error (knowledge of results) on previous trials could have been used to initiate the next primary movement on the next trial.

After the exposure period, the prisms were reset to zero diopters, the subjects were told that any distortion was no longer present to minimize deliberate carryover of recalibration strategies, the two recalibration tests, and then the three realignment tests were repeated, 10 trials for each kind of test. The predicted posttest adaptive change from pretest baseline is opposite the direction of prismatic displacement for the proprioceptive shift, total shift tests, and recalibration tests, but in the direction of prismatic displacement for the visual shift test (Redding et al. 2005; Redding & Wallace, 1988c, 1998, 2000; Welch, 1978).

All measurements were to the nearest degree. Throughout the experiment the subjects' head was constrained by the chinrest and the head was visually monitored by the experimenter to correct any changes in position. Long experience has demonstrated that such head constraint is
adequate for present purposes. Pointing movements, in both exposure and tests, were paced by a metronome set to beat every 1.5 s (.67 beats/s); that is, one trial every 3 s. Subjects began an outward movement on one beat, completed it on the next beat, and immediately began a backward movement, which was completed on the third beat. The third beat served as the signal to begin the next outward movement, and so on for the out-and-back movement cycles, with each segment of the cycle performed in about 1.5 s. With these instructions, subjects achieved a smooth cycle of movements. The same pointing rate was employed for exposure trials, for realignment tests where pointing was required (i.e., proprioceptive shift and total shift tests), and for recalibration tests.

Results and Discussion

Direct effects of the prismatic distortion on performance during exposure are not directly commensurable with calibration aftereffects and alignment aftereffects of prism exposure (but see Redding & Wallace, 1993). For this reason the three kinds of measures were analyzed separately, before considering their joint implications. Data are reported in degrees left (-) or right (+) of objective straight ahead. However, the data may be converted to cm at the 74 cm distance to the back of the apparatus by a constant multiplier of 1.31. For an average reach of 50 cm the conversion factor is .87.

The main results, presented in detail in the following subsections, were as follows. During prism exposure there was no large difference in terminal error between exposure starting position groups and terminal error decreased over trials for both starting positions, showing overcompensation toward the end of exposure. Exposure terminal error was less and decreased more rapidly over trials when the immediately preceding recalibration pretest matched the exposure starting position, showing benefit from pre-calibration. Recalibration aftereffects were largest when the starting position for the recalibration posttest and preceding exposure matched, showing associative generalization. Realignment aftereffects were almost entirely localized in the visual eye-head system and were unrelated to similarity manipulation of the recalibration tests.

Exposure Performance. Exposure performance was expressed as terminal pointing error, the difference in degrees between terminal finger position and the objective straight ahead target. Analysis by individual trial was found to violate statistical model assumptions. The data for the 30 trials were, therefore, averaged for blocks of five trials each. These blocked data are displayed in Figure 3 as a function of exposure trial block, exposure starting position, and order of starting position in pre-post exposure recalibration tests. A Exposure Starting Position by Exposure Trial Block by Order of Recalibration Tests analysis of variance was performed on the blocked terminal error data.

The main effect of Exposure Starting Position, $F(1,28) = 5.79$, $p = .023$, indicated that terminal error averaged over trial blocks was slightly greater for the proximal starting position (1.7 deg) than for the distal starting position (1.3 deg). There was no main effect of Order of Recalibration Tests, $F(1,28) = 2.62$, $p = .117$, but the Exposure Starting Position by Order of Recalibration Tests, was statistically significant, $F(1,28) = 31.52$, $p < .001$. Average terminal error was smallest when starting position during exposure and for the immediately preceding recalibration test were the same. The distal exposure starting position with proximal-then-distal pretest order mean terminal error (1.1 deg) was almost identical to that for the proximal exposure starting position with distal-then-proximal pretest order (1.2 deg). Mean terminal error was largest for the distal exposure starting position with distal-then-proximal pretest order (1.6 deg).
and for the proximal exposure starting position with proximal-then-distal pretest order (2.2 deg). These results suggest practice with the same starting position immediately prior to exposure enhanced exposure performance by calibration transfer: the similar task prior to exposure “pre-calibrated” the exposure task.

![Figure 3](image)

**Figure 3.** Terminal pointing error during exposure was measured from objective straight ahead as a function of pointing trial, exposure starting position (proximal or distal), and order of starting position in pre-post recalibration tests: proximal-then-distal (P-D) or distal-then-proximal (D-P). The objective target was positioned straight ahead (0 deg), while the virtual target appeared displaced 11.4 deg to the right. Data for the thirty trials are shown averaged for blocks of five trials. Error bars denote standard errors. (Experiment 1)

As can be seen in Figure 3, terminal error averaged 5.4 deg for the first block of trials, about 47 percent of the 11.4 deg optical displacement\(^1\). Terminal error then decreased over blocks of trials, \(F(5,140) = 411.02\), \(p < .001\), more rapidly when the starting position of the immediately preceding pretest matched that of exposure, \(F(5,140) = 15.28\), \(p < .001\). Therefore, the benefit of pre-calibration extended to more rapid target achievement during exposure. By block five (trials 20-25) all groups were performing with near zero terminal error. However, during the last five trials (block 6) subjects tended to show an average error to the left of the target, overcompensation for the rightward prismatic displacement. This pattern of overcompensation has been interpreted as indicating the deployment of a side-pointing strategy

\(^1\)Such first trial “adaptation” can be attributed to ordinary motor undershoot and visual capture that reduces the effective prismatic displacement during exposure (Redding & Wallace, 2003b, 2004). Further discussion of these effects is beyond the present scope.
(target recalibration) to compensate for error on previous trials (Redding & Wallace, 1993). Persistence of such a strategy in the face of developing realignment leads to overcompensation.

Recalibration Aftereffects. Examination of the pre-exposure recalibration pretests revealed no significant sources of variance involving trials ($p > .15$). Therefore, averaging over trials did not misrepresent the data. The only significant source of variance in this analysis was the Exposure Starting Position by Recalibration Test interaction, $F(1,28) = 4.51$, $p = .043$. For the groups that subsequently received the proximal starting position during exposure the average performance on the proximal recalibration pretest was to the left of the objectively straight ahead target (-.22 deg) while performance for the distal recalibration pretest was right of the target (.03 deg). For the groups that subsequently received the distal starting position average performance was to the left of the target for both the proximal (-.18 deg) and distal (-.31 deg) recalibration pretests.

While these differences are small, they do indicate that the baselines were not exactly equivalent prior to prism exposure. Consequently, pretest-posttest change scores (see Method) were calculated to minimize effects of non-equivalence. All subsequent analyses were performed on these recalibration aftereffect measures.

An Exposure Starting Position (proximal, distal) by Recalibration Test (proximal or distal starting position) by Order of Recalibration Tests (proximal then distal, distal then proximal) analysis of variance was performed on the data. The only significant sources of variance ($p > .10$) were the main effect of Exposure Starting Position, $F(1,28) = 5.80$, $p = .023$, the Exposure Starting Position by Order of Recalibration Tests interaction, $F(1,28) = 5.95$, $p = .021$, and the predicted Exposure Starting Position by Recalibration Test interaction, $F(1,28) = 67.99$, $p < .001$. 

![Figure 4](image1.png)

Figure 4. Recalibration aftereffects averaged over order of recalibration tests. Aftereffects of prism exposure with proximal or distal starting positions are shown for recalibration tests with proximal or distal starting positions. Error bars denote standard errors. (Experiment 1)

![Figure 5](image2.png)

Figure 5. Recalibration aftereffects averaged over recalibration test. Aftereffects of prism exposure with proximal or distal starting positions are shown for proximal then distal and distal then proximal orders of the post-exposure recalibration tests. Error bars denote standard errors. (Experiment 1)
On average, recalibration was slightly greater for the distal starting position during exposure (3.8 deg) than for the proximal starting position during exposure (3.4 deg). As illustrated in Figure 4, the primary prediction was confirmed. Aftereffects were largest when the starting position for exposure and recalibration post-test matched, showing associative generalization. As illustrated in Figure 5, recalibration also tended to be largest when the first post-exposure recalibration test matched the immediately preceding exposure starting position, especially for the distal starting position exposure.

As predicted, generalization of recalibration was largest when training (exposure) was most similar to test (post-exposure). Moreover, additional evidence of associative generalization appeared in that recalibration was larger when the test was similar to the immediately preceding exposure without an intervening dissimilar test.

Realignment Aftereffects. The only significant source of variance in the pre-exposure realignment pretests was the Exposure Starting Position by Recalibration Test Order by Realignment Test by Trial interaction, $F(18,504) = 1.64$, $p = .047$. Examination of these data did not reveal any pattern that would be misrepresented by averaging over trials and the usual pre-post change scores (see Method) were calculated to minimize any effects of non-equivalence among groups. All subsequent analyses were performed on these realignment aftereffect measures.

As can be seen in Figure 6, the total shift (TS) measure and the sum of visual and proprioceptive shift measures ($VS + PS$) had nearly identical values (4.1 deg), $F(1,28) = .08$, $p = .780$. There were no other significant effects in this analysis ($p > .18$), indicating that the two measures were not reliably different within or between groups and, therefore, unrelated to recalibration. Such additivity provides a converging check on the assumption that these aftereffects measure realignment, independent of contributions from strategic control processes such as memory of movements practiced during prism exposure (i.e., recalibration) that might transfer to the post-exposure tests (Redding, 1978; Redding & Wallace, 1988a, 1988b, 1993).

![Figure 6](image_url)
Figure 6 also displays the data for the component tests of visual shift (VS) and proprioceptive shift (PS). On average, visual aftereffects in the eye-head system (3.1 deg) were larger than proprioceptive aftereffects in the hand-head system (1.0 deg), $F(1,28) = 91.28, p < .001$, and the absence of any other significant source of variance in this analysis ($p > .19$) indicated that visual shift was greater than proprioceptive shift by about the same amount for all groups: again, unrelated to recalibration. These realignment aftereffect results replicate many previous studies (e.g., Redding & Wallace, 1993, 2000; Uhlarik & Canon, 1971); realignment aftereffects of prismatic displacement are localized in the visual eye-head system when visual feedback is delayed (i.e., terminal exposure).

As predicted, total realignment was not affected by the similarity manipulation between exposure and recalibration test. Also as predicted, the components of realignment were largely affected by the exposure feedback manipulation that only marginally affected recalibration. Correlational analysis suggested that recalibration aftereffects were poorly related to total alignment aftereffects, $r = .28, p = .147$, although total alignment aftereffects were correlated with the sum of component (VS + PS) alignment aftereffects, $r = .65, p = .003$. Therefore, recalibration and total realignment aftereffects seem to have little in common, although both measures ostensibly involve the same target-pointing behavior, but total realignment aftereffects have much in common with components of realignment. This is further evidence that realignment is an adaptive response separable from adaptive recalibration during exposure (Redding & Wallace, 1993, 1997b, 2001, 2002).

Comparison of Aftereffect Magnitude. Contrary to prediction, average realignment aftereffects (4.1 deg) were surprisingly larger than average recalibration aftereffects (3.6 deg), $F(1,28) = 10.81, p = .003$. Importantly, there were no other significant sources of variance in this analysis ($p > .05$), indicating that the difference between aftereffects was consistent across conditions\(^1\). If realignment is hidden from recalibration, as hypothesized, realignment should have added to recalibration producing larger apparent recalibration than realignment. Although this result does not negate the primary finding of differential generalization for the two adaptive processes, it nevertheless is puzzling.

A possible explanation of this discrepancy is that recalibration aftereffects were underestimated with the present procedure. Informing the subjects immediately after exposure that the distortion had been removed would tend to terminate the side-pointing strategy that appeared as overcompensation at the end of exposure (see Figure 3) and any other deliberate calibration strategy: saying, in effect, that the task no longer required such strategic recalibration. Indeed, subjects may have even compensated by undershooting the target on the post-exposure recalibration tests because they had just been overshooting the target. In the second experiment such information was delayed until after the recalibration tests had been concluded to provide a test of this interpretation. Despite this oversight in the present experiment, the fact that even knowing that the distortion had been removed subjects still produced different recalibration aftereffects as a function of similarity between exposure and test clearly demonstrates that there is more to recalibration than “conscious correction”.

\(^1\)This difference was present between realignment (4.2 deg) and recalibration (3.5 deg) even for the group receiving proximal starting position exposure and proximal then distal order of the recalibration tests which might have been expected to show similar aftereffects due to the apparent similarity in starting position for recalibration and realignment tests. In fact, limb posture for pointing on upper and lower levels of the apparatus was quite different.
Experiment 2

The first experiment confirmed the associative nature of recalibration, distinct from non-associative realignment. Generalization of recalibration depended upon similarity of training (exposure) and test (post-exposure) conditions, while generalization of realignment depended upon the involved spatial maps. Experiment 2 was designed to identify the different generalization gradients for recalibration and realignment.

Figure 7 illustrates the predicted generalization gradients for recalibration and realignment. Bedford (1989, 1993b) introduced the concepts of minimal, intermediate, and maximal constraint to describe non-linear generalization, best-fit linear rule, and rigid uniform shift, respectively. Associative recalibration falls within the class of cognitive learning where constraints are minimal and it is possible to remap a single corresponding point in spatial maps. Transformational realignment falls within the class of perceptual learning that is maximally constrained by the regularity that Euclidian space is uniform regardless of how it is represented. Therefore, learning a spatial remapping of a single corresponding point in different spatial maps may produce a rigid transformational shift in the mapping of all points in the spatial maps. However, transformational remapping may also be limited by existing mappings of untrained corresponding points, in which case the perceptual-motor system settles on the intermediate constraint of finding the best-fit linear mapping rule.

Figure 7. Constraints on generalization as given in Bedford (1989). Associative recalibration is minimally constrained, generalization being a non-linear function of similarity between training and test values. Generalization of transformational realignment may be maximally constrained by the locally uniform nature of space or intermediately constrained by a best-fit linear rule accommodating both old and new learning.
The second experiment was designed to produce the different generalization gradients for recalibration and realignment. Table 2 illustrates the logic of the experimental procedure. As in the first experiment, the first three and last three experimental events (E1, E2, E3, E7, E8, E9) were pre-post exposure tests of visual, proprioceptive, and visual-proprioceptive straight ahead: visual shift (VS), proprioceptive shift (PS), and total shift (TS). The only difference in these tests from the first experiment was that the total shift test involved three target positions: left, straight ahead, and right. Because this test required coordination of the visual and proprioceptive spatial maps evoked by exposure target pointing, but was otherwise largely different from exposure conditions (e.g., in limb posture and starting position), it was expected to measure realignment and aftereffects for the three post-exposure target positions was expected for conform to linearly constrained generalization (see Figure 7).

Table 2
Illustration of the Experimental Procedure for Experiment 2.

<table>
<thead>
<tr>
<th>Realignment Pretests</th>
<th>Recalibration Pretests</th>
<th>Prism Exposure Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>E2</td>
<td>E3</td>
</tr>
<tr>
<td>VS</td>
<td>PS</td>
<td>TS</td>
</tr>
<tr>
<td>DTP</td>
<td>DTP</td>
<td>T or C</td>
</tr>
</tbody>
</table>

Recalibration Posttests
<table>
<thead>
<tr>
<th>Realignment Posttests</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Feedback</td>
</tr>
<tr>
<td>E6</td>
</tr>
<tr>
<td>DTP</td>
</tr>
<tr>
<td>TS</td>
</tr>
</tbody>
</table>

Note: E: (Event) Ordinal position of experimental events. VS: (Visual Shift) Non-manual adjustment to visual straight-ahead. PS: (Proprioceptive Shift) Manual pointing to straight-ahead without vision. TS: (Total Shift) Manual pointing to visible leftward, straight-ahead, and rightward targets without feedback. Order of the three realignment tests was random, as was the order of the three positions tested with the total shift measure. DTP: (Distal Target Pointing) Manual pointing to visible straight-ahead target from distal starting position; leftward, straight-ahead, and rightward targets for pretest and posttest, but single straight-ahead target for exposure. Order of the three positions for recalibration testing was random and feedback was not available. T: (Terminal visual feedback) Only the tip of the finger at the terminus of the pointing movement was visible during exposure. C: (Concurrent visual and proprioceptive feedback) After the starting position, the moving finger was visible over the entire movement path during exposure.

Pointing toward a straight-ahead target from the distal starting position was required during exposure (E5). Different groups received terminal visual feedback (T) or concurrent visual and proprioceptive feedback (C) during exposure. Delayed visual feedback (terminal exposure) at the end of a pointing movement was expected to produce realignment largely localized in the visual eye-head sensory-motor system, as in the first experiment, while early visual feedback (concurrent exposure) during the point movement was expected to produce realignment largely localized in the proprioceptive hand-head sensory-motor system (e.g., Redding & Wallace, 1993, 2000; Uhlarik & Canon, 1971). Local realignment was measured by the component visual and proprioceptive shift tests.

The fourth and sixth experimental events (E4, E6) illustrated in Table 2 were identical to the intervening prism exposure (E5) except for the absence of feedback, knowledge of results, and, of course, prismatic displacement. These pre-post exposure tests also involved three target
positions: left, straight ahead, and right. Because this test was identical to the exposure task, it was expected to measure recalibration and aftereffects for the three post-exposure target positions was expected for conform to non-linear generalization (see Figure 7).

Finally, informing subjects that the prismatic displacement had been removed was delayed until after the recalibration posttests and before the realignment posttests. If the magnitude of recalibration aftereffects were underestimated in the first experiment by termination of deliberate strategies deployed during exposure, then recalibration aftereffects were expected to exceed in magnitude realignment aftereffects, as predicted by the automatic nature of realignment.

**Method**

The method for the second experiment was similar to that of Experiment 1 with the following exceptions. Thirty-two new subjects were recruited from the same source with the same restrictions and ethical treatment constraints. Only the distal starting position was used for exposure (see Figure 2) and for pre-post recalibration tests because this condition produced the largest amount of recalibration in the first experiment. Subjects were not informed that the prismatic displacement had been removed until after the recalibration posttests had been concluded. Resetting the prisms to zero diopters immediately after conclusion of the exposure period was covered by a sham story about “adjusting the goggles”. The most important difference from Experiment 1 was the introduction of three tests targets for the pre-post total shift realignment test and recalibration test. Test target positions were 5 deg left and right of objective straight ahead and included the straight ahead position employed during exposure. Subjects pointed 10 times to each of the three targets in a random order.

![Figure 8. Exposure Arrangement.](image)

**Figure 8. Exposure Arrangement.** Exposure conditions are illustrated in a top-down schematic view, showing the straight-line movement path from the distal starting position toward the target. The occluding shelf was positioned to afford view of the full movement path (concurrent feedback) or only the tip of the pointing finger at the terminus of the movement (terminal feedback), but starting position was not visible for either condition. The limit of the occluding shelf varied, depending upon the subject’s maximal reach. The illustration assumes an average reach of 50 cm. (Experiment 2)
Successive groups of 16 subjects each were tested with terminal and concurrent feedback. The exposure arrangements for terminal and concurrent feedback are schematically illustrated viewed from above in Figure 8. The limit of the occluding shelf varied, depending upon the subject’s arm length, and the illustrated arrangement assumes an average arm length of 50 cm. For both groups, the starting position for target pointing during exposure and recalibration tests was the subjects’ right hand positioned on the upper level of the apparatus 37 cm in front of their body trunk, against the distal side of the box (see Figure 1). The subjects’ limb was not visible in the starting position.

Results and Discussion

As in Experiment 1, direct effects, recalibration aftereffects, and realignment aftereffects are examined separately before considering their joint implications. The main results, presented in detail in the following subsections, were as follows. Terminal error during exposure decreased over trials reaching target achievement between trials 10-20 and overcompensation tended to occur in later trials. Recalibration aftereffects were largest for the training position, showing non-linear generalization. Total realignment aftereffects were fit by a zero-slope linear function, showing global generalization. Realignment aftereffects were predominately localized in the visual eye-head system and proprioceptive hand-head system with terminal and concurrent exposure, respectively, and were not related to performance on the recalibration tests.

Figure 9. Terminal pointing error during exposure was measured from objective straight ahead as a function of pointing trial and feedback condition (terminal or concurrent). The objective target was positioned straight ahead (0 deg), while the virtual target appeared displaced 11.4 deg to the right. Data for the thirty trials are shown averaged for blocks of five trials. Error bars denote standard errors. (Experiment 2)
Exposure Performance. Average terminal error during exposure is displayed in Figure 9 as a function of feedback condition and exposure trial block. As in Experiment 1, terminal error in the first trial block was only about 45 percent of the 11.4 deg prismatic displacement and decreased over successive trial blocks in a negatively decelerated fashion, \( F(5,150) = 367.89, p < .001 \), reaching target achievement between trials 10-15 (block 3) for concurrent feedback and between trials 15-20 (block 4) for terminal feedback. Averaged over trial blocks, terminal error was smaller for concurrent feedback (.9 deg) than for terminal feedback (1.3 deg), \( F(1,30) = 7.68, p = .009 \). As can be seen in Figure 8 and supported by the Exposure Feedback Condition by Trial Block interaction, \( F(5,150) = 3.70, p = .003 \), the smaller average terminal error appears largely due to greater overcompensation with concurrent feedback, consistently for the last three trial blocks. Subjects receiving terminal feedback also tended to show overcompensation, but only for the last two trial blocks (cf. Redding & Wallace, 1993).

Recalibration and Realignment Aftereffects. Examination of the recalibration pretests revealed differences among target positions, \( F(2,60) = 5865.37, p < .001 \), and an interaction of test and trial, \( F(18,540) = 1.90, p = .014 \), but no other statistically reliable effects (\( p > .128 \)). On average, pretest pointing to the leftward target was accurate (-5.0 deg), while straight ahead targets showed small leftward bias (-0.1 deg) and the rightward target showed a small rightward bias (5.1 deg). Examination by trial revealed no pattern that would compromise these averages. Similar examination of the total realignment pretests revealed only differences among target positions, \( F(2,60) = 5649.35, p < .001 \), and no other statistically reliable sources of variance (\( p > .128 \)). Averaged over trials, pretest pointing to the left and straight ahead targets showed small leftward biases (-5.1 and -0.2 deg, respectively), while the rightward target showed a small rightward bias (5.2 deg).

Therefore, averaging over trials did not misrepresent the data for either recalibration or total realignment pretests. However, bias for both recalibration and realignment pretests suggests some nonequivalence of baselines for the three target positions. Consequently, pretest-posttest change scores (see Method) were calculated for each target position to minimize effects of nonequivalence for both recalibration and realignment target position baselines. All subsequent analyses were performed on these aftereffect measures.

Analysis of the total realignment aftereffects revealed a main effect of Exposure Feedback Groups, \( F(1,30) = 17.31, p < .001 \), and an interaction of Exposure Feedback Groups by Target Positions, \( F(2,60) = 90.53, p < .001 \). The total realignment aftereffect was larger for concurrent feedback (5.7 deg) than for terminal feedback (4.7 deg). Also, as illustrated in Figure 10, terminal feedback aftereffects were a negative linear function of target position, \( y = -.19x + 4.68, R^2 = .99 \), while concurrent feedback aftereffects were a positive linear function of target position, \( y = .18x + 5.67, R^2 = .99 \). These slope coefficients for total realignment aftereffects are small deviations from predicted zero slope functions. Moreover, the deviations reasonably arose from a differential predominance of trained and untrained points to the left and right of the apparent straight ahead for predominately visual and proprioceptive realignment produced by terminal and concurrent feedback, respectively (see below).
The differential effects of terminal and concurrent feedback on total realignment were arguably produced by the different directions of coordination (guidance) between visual eye-head and proprioceptive hand-head sensory-motor systems evoked by the differential availability of visual feedback (Redding & Wallace, 1990, 1992, 1994, 1997a, 2000). When visual feedback is available early in the pointing movement (concurrent feedback), the visual guidance that initiated movement is largely maintained throughout the movement. Consequently, the visual system sets the standard for spatial remapping and realignment is largely localized in the guided proprioceptive hand-head system. However, when visual feedback is delayed until the end of the pointing movement (terminal feedback) the initial direction of guidance is reversed: the eyes respond to proprioceptive signals from the non-visible limb. Consequently, the proprioceptive system sets the standard for spatial remapping and realignment is largely localized in the guided visual eye-head system. The different directions of guidance (eye-to-limb and limb-to-eye) and consequential realignment produce different regions of trained points in the spatial map for the guided (realigned) system.

Figure 11 illustrates the pair-wise training points for visual and proprioceptive spatial maps when the guided visual sensory-motor system is realigned with the guiding proprioceptive sensory-motor system: that is, with terminal feedback. As illustrated by left to right stages of adaptation in Figure 11, veridical proprioception forces realignment of visual straight ahead to correspond with the apparent position of the target: that is, the spatial location of visual points between pre-exposure straight ahead and post-exposure straight ahead are changed. Therefore, visual points to the left of the new post-exposure straight ahead are trained, while points to the
right of the new post-exposure straight ahead are untrained. Therefore, the best-fit linear function in Figure 10 has a negative slope, down from left to right.

**Visual (Guided) System**

SA = Visual Straight Ahead  
AT = Apparent Target Position  
AH = Apparent Hand Position

**Visual (Guiding) System**

SA = Visual Straight Ahead  
AT = Apparent Target Position  
AH = Apparent Hand Position

**Proprioceptive (Guiding) System**

SA = Proprioceptive Straight Ahead  
VH = Vertical Hand Position

**Proprioceptive (Guided) System**

SA = Proprioceptive Straight Ahead  
VH = Vertical Hand Position

Figure 11. Illustration of trained visual-proprionicceptive pairs where the proprioceptive hand-head sensory-motor system guides and sets the veridical standard for spatial remapping of the guided visual eye-head sensory-motor system. Reading from left to right, visual straight ahead is shifted from the objective, pre-exposure position toward the rightward prismatically displaced target by signals from the proprioceptive system until post-exposure remapped points occupy the interval to the left of the new visual straight ahead, while untrained points occur to the right of the new visual straight ahead.

Similarly, Figure 12 illustrates the pair-wise training points for visual and proprioceptive spatial maps when the guided proprioceptive sensory-motor system is realigned with the guiding visual sensory-motor system: that is, with concurrent feedback. As illustrated by left to right stages of adaptation in Figure 12, unchanging vision forces realignment of proprioceptive straight ahead to correspond with the apparent rightward position of the target: that is, the hand in the straight ahead position now feels positioned rightward and must be positioned leftward to feel straight ahead. The spatial locations of proprioceptive points are changed between pre-
exposure straight-ahead and post-exposure straight-ahead. Therefore, proprioceptive points to the right of the new post-exposure straight ahead are trained, while points to the left of the new post-exposure straight ahead are untrained. Therefore, the best-fit linear function in Figure 10 has a positive slope, up from left to right.

This analysis suggests that the slope of the linear constraint depends upon the locus of realignment: positive slopes arise from realignment of the proprioceptive hand-head system, while negative slopes arise from realignment of the visual eye-head system. In contrast to Bedford’s (1989) procedure where discrete training points could be isolated, the usual prism exposure involves multiple training pairs. Therefore, under the conditions of the present experiment, maximally constrained results (zero slope) can only arise when exposure conditions are such as to produce equal amounts of both kinds of realignment. Therefore, the data were combined for exposure groups to obtain an unbiased estimate of realignment generalization. Such combination was also justified because analysis of the recalibration aftereffects revealed no statistically reliable effects involving exposure groups \( p > .24 \), another indication of a fundamental difference between realignment and recalibration.

![Graph](image)

Figure 13. Recalibration and realignment aftereffects are shown as a function of post-exposure target position (-5° left, straight ahead, 5° right) and fitted with non-linear (second-order polynomial) and linear functions, respectively. Error bars denote standard errors.

Generalization data for both recalibration and total realignment aftereffects are displayed in Figure 13. Recalibration aftereffects were largest for the straight-ahead training point, \( F(2,60) = 14.53, \ p < .001 \), and not reliably different for the two untrained test points, \( F(1,30) = 0.07, \ p = .796 \). As can be seen from the standard error bars in Figure 13, recalibration aftereffects were well fit by a non-linear (second order polynomial) function, \( y = -0.05x^2 + .01x + 6.28 \), \( R^2 = .99 \),
which approximates the associative generalization gradient (see Figure 7). In contrast, total realignment aftereffects were almost the same value for all test positions, \( F(2,60) = 0.46, p = .632 \), and were well described by a near-zero slope linear function, \( y = -.01x + 5.18 \), which matches maximally constrained transformational generalization (see Figure 7).

Correlational analysis indicated that recalibration and total realignment aftereffects shared little in common, \( r = .31, p = .043 \), but total realignment aftereffects shared much in common with component measures (VS + PS) of realignment, \( r = .82, p < .001 \). Note that the small, but significant correlation between recalibration and realignment aftereffects probably reflects the more accurate measurement of recalibration in this experiment compared to the first experiment and the inclusion of hidden realignment in recalibration measures.

Examination of Figure 13 suggests that recalibration aftereffects did not generalize to the non-trained positions tested\(^1\) and that aftereffects at these positions were entirely due to realignment, as predicted by the automatic nature of realignment. Analysis of the difference between recalibration and realignment aftereffects for leftward (-.2 deg), straight ahead (1.2 deg), and rightward (-.1 deg) target positions revealed an effect of Position, \( F(2,62) = 8.69, p < .001 \), but this effect was entirely due to the straight ahead position because analysis showed that the differences for leftward and rightward positions alone was not statistically reliable, \( F(1,31) = .10, p = .757 \).

The best estimate of the relative contributions of recalibration and realignment to adaptation, therefore, is obtained by comparing aftereffects for the trained position. Recalibration aftereffects (6.3 deg) showed 55 percent compensation for the 11.4 deg prismatic displacement, while realignment aftereffects (5.1 deg) showed 45 percent. The difference of 10 percent compensation can be attributed to recalibration alone. It seems likely that larger contributions from recalibration can be expected at early stages of exposure, before developing realignment has decreased the need for strategic recalibration. Further research can establish the relative contributions of realignment and recalibration under various exposure and training conditions.

Clearly, recalibration and realignment aftereffects show different generalization. Our findings replicated Bedford while using a more standard prism adaptation procedure.

Recalibration aftereffects follow the typical non-linear generalization gradient along similarity dimensions of traditional associative learning (Bedford, 1993a). Recalibration is unconstrained and this kind of learning can occur even for arbitrary pair-wise points in associated spatial maps. In contrast, realignment aftereffects are constrained by a linear rule, finding the best possible linear function fit for both trained and untrained pair-wise points in the relevant spatial maps (Bedford, 1989, 1993a, 1993b, 1999). We conclude that calibration and realignment are, then, fundamentally different kinds of adaptive processes, but both are evoked by the common prism adaptation procedure.

Component Realignment Aftereffects. There were no significant sources of variance in a Test by Trial analysis of pre-exposure realignment baseline tests (\( p > .162 \)). Nearly identical values were found for the average total shift (-.05 deg), proprioceptive shift (-.09 deg), and visual shift (.04 deg) pretests. Therefore, averaging over trials did not misrepresent the data and, the usual pre-post change scores (see Method) were calculated to control for the small initial

---

\(^1\)Of course, if positions closer to the training position were tested, they could be expected to show larger recalibration aftereffects than corresponding realignment aftereffects. The lateral extent of the task-work space for recalibration may not be large enough to encompass 10 deg of visual space.
differences in bias among the tests. All subsequent analyses were performed on these aftereffect measures.

The average total shift (TS) measure (5.2 deg) and the sum of visual and proprioceptive shift measures (VS + PS) had nearly identical values (5.1 deg), $F(1,30) = .52, p = .475$, and the two measures did not interact with exposure groups, $F(1,30) = .18, p = .678$. Such additivity provides a converging check on the assumption that these aftereffects measure realignment, independent of contributions from strategic control processes such as memory of movements practiced during prism exposure (i.e., recalibration) that might transfer to the post-exposure tests (Redding, 1978; Redding & Wallace, 1988a, 1988b, 1993).

Figure 14 displays the data for the component tests of visual shift (VS) and proprioceptive shift (PS) for terminal and concurrent feedback groups. As can be seen in Figure 14 and supported by the Exposure Group by Component Test interaction, $F(1,30) = 236.59, p < .001$, visual shift (3.6 deg) was larger that proprioceptive shift (1.0 deg) with terminal feedback, while proprioceptive shift (4.6 deg) was larger that visual shift (1.1 deg) with concurrent feedback. On average, proprioceptive aftereffects in the hand-head system (2.8 deg) were larger that visual aftereffects in the eye-head system (2.3 deg), $F(1,30) = 5.59, p = .025$, and concurrent feedback (2.8 deg) produced larger aftereffects that terminal feedback (2.3), $F(1,30) = 9.24, p = .005$.

![Figure 14. Realignment aftereffects are shown separately for the visual shift (VS) test for realignment in the eye-head system and the proprioceptive shift (PS) test for realignment in the hand-head system as a function of terminal or concurrent feedback during exposure. Error bars denote standard errors.](image)

These realignment aftereffects replicate many previous studies (e.g., Redding & Wallace, 1993, 2000; Uhlarik & Canon, 1971). Realignment aftereffects of prismatic displacement are
localized in the visual eye-head system when visual feedback is delayed (i.e., terminal feedback) and in the proprioceptive hand-head system when visual feedback becomes available early in pointing movements (i.e., concurrent feedback). It is important to note that recalibration aftereffects were the same despite these differences in realignment aftereffects for exposure conditions: further evidence for distinctly different kinds of adaptive processes.

Conclusions

These experiments clearly demonstrate that both perceptual and cognitive adaptive processes suggested by Bedford in her reduced prism adaptation paradigm also occur in the common prism adaptation paradigm. Reduced exposure conditions are not necessary to produce realignment and adaptation is not entirely due to recalibration. We conclude that the two kinds of processes can be isolated and compared by manipulating the conditions for generalization.

Recalibration aftereffects generalized associatively as in Bedford (1993a) and, moreover, were largest when post-exposure conditions were similar to exposure conditions in limb posture (Experiment 1) and in training position (Experiment 2). When similarity between exposure and post-exposure conditions was parametrically manipulated recalibration aftereffects demonstrated the generalization gradient of traditional associative learning (Experiment 2). Confirming evidence that the present procedures produced measures of recalibration is the beneficial effect on exposure adaptation when the pre-exposure recalibration test matched exposure conditions, providing pre-calibration for the exposure task (Experiment 1).

In contrast, realignment aftereffects generalized non-associatively, appearing in undiminished magnitude regardless of the dissimilarity between exposure and post-exposure conditions so long as the exposure spatial maps were also measured in post-exposure (Experiment 1). Realignment aftereffects also conformed to the best-fit linear rule found by Bedford for combining old and new learning (Experiment 2). Finally, the nature of realignment depended upon the manner in which spatially discordant sensory-motor systems were coordinated, upon the direction of coordination evoked by exposure conditions (Experiment 2).

Studies showing generalization of prism adaptation specific to conditions of exposure (e.g., Baraduc & Wolpert 2002; Fernández-Ruiz et al. 2000; Field et al. 1999; Kitazawa et al. 1997; Martin et al. 1996b) reflect associative generalization of cognitive recalibration along similarities between exposure and post-exposure conditions. Generalization of realignment (e.g., Bedford, 1989; Redding & Wallace, 1993, 1997a, 2002) reflects the perceptual process of spatial mapping between spatially discordant sensory-motor maps, a remapping process that is constrained by the locally uniform nature of Euclidian space. Recalibration and realignment are functionally distinct kinds of response to prism exposure both evoked in common prism adaptation.

The automatic, hidden nature of alignment means that it is almost undetectable in ordinary perceptual-motor behavior, whereas calibration is deceptively large in its contribution to everyday spatial behavior. Consequently motor control theorists have, at least implicitly, assumed that alignment of spatial maps is included in calibration. Perhaps only the prism adaptation procedure could have revealed the separable nature of the two adaptive processes. Calibration and alignment are distinct processes that have different activating conditions and different generalization functions (Redding & Wallace, 1997a, 2001, 2002, 2003a). Theories of motor control must make separate provisions for the two kinds of adaptive processes.
The prism adaptation paradigm is uniquely suited for detecting realignment (or perceptual learning), but it is also a powerful tool for investigating recalibration (or cognitive learning). However, the fact that the usual prism exposure evokes both adaptive processes means that application of the procedure must include methodology for identifying and measuring the kinds of adaptation that occur (Redding et al. 2005). Bedford’s (1989, 1993a) reduction method or the present method of assessing additivity of local aftereffects are effective means for isolating realignment, but no complimentary methods have been developed for isolating recalibration during prism exposure, perhaps because realignment is unavoidably part of prism adaptation.

For example, in applications of prism adaptation to the study of ordinary perceptual-motor control (e.g., Martin et al. 1996b; Kitazawa et al. 1997) one cannot simply assume that recalibration alone is responsible for adaptation, even when the primary manipulation is similarity of exposure and post-exposure conditions: separate aftereffect measures of the involved spatial maps must also be obtained to assess contributions of realignment. Conversely, applications of prism adaptation to ameliorate unilateral neglect (e.g., Frassinetti et al. 2002; Rossetti et al. 1998) cannot conclude that the source of the therapeutic effect lies in realignment without converging manipulations of similarity between exposure and post-exposure tests to assess recalibration contributions (Redding, Rossetti, & Wallace, 2005; Redding & Wallace, in press). The utmost caution must also be exercised in interpreting error reduction during prism exposure: such adaptation reflects joint and even conflicting contributions of recalibration and realignment (Redding & Wallace, 1993, 1996, 1997b).

Finally, we reiterate and extend Bedford’s caution (1993b; see also 1994, 2001) concerning computer devices to simulate prismatic transformations in virtual reality (e.g., Baraduc & Wolpert, 2002; Ingram, van Donkelaar, Cole, Vercher, Gauthier, & Miall, 2000). Clower and Boussaoud (2000) have shown that aftereffects appeared when the prism exposure period provided actual visual feedback about limb position, but not when feedback was computer generated, even though performance during prism exposure was identical for the two conditions. Discordance detection depends upon the object-unity assumption (Welch, 1994; Welch & Warren, 1980): the assumption that coordinates in different intrinsic spatial representations come from the same object in extrinsic space. Several justifications of this assumption have been proposed (Bedford, 1993b, 1994, 2001; Radeau, 1994; Redding, 2001) and Redding and Wallace (1997a) discuss this correspondence problem at some length.

The caution here is that virtual reality simulations may not produce spatial realignment because conditions for the object-identify assumption are not present (see also Bedford, 1993b, 1999). Moreover, when aftereffects do occur in such simulations (Baraduc & Wolpert, 2002) they may reflect generalization of strategic recalibration rather than realignment, cognitive rather than perceptual learning (Bedford, 1992a). Also, simulations may deploy different coordination strategies that affect discordance detection and spatial realignment (cf. Ingram et al., 2000, and Redding, Rader, & Lucas, 1992). Exactly how virtual reality simulations are related to prism adaptation remains to be determined.

References


