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Effects of Error Production on Prism Adaptation Generalization During Goal-Oriented Locomotion

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by

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Abstract

Prism adaptation is a unique and effective way to study the process of visuomotor learning. In particular, studying how prism adaptation generalizes can elucidate exactly what the vision and motor systems are learning. In this study, the transfer of prism adaptation from a walking task to a target-pointing task was examined. One group was instructed to have error-free performance during the prism exposure adaptation task while another group was permitted to walk naturally, allowing for error. Participants were wearing either left or rightward deviating prisms. It was predicted that groups that were permitted to perform with errors would adapt more and therefore show higher levels of generalization to a target-pointing task. Error-production was not found to have an effect on the participants' ability to adapt. However, participants did show effects of the prisms as their errors post-test were opposite of their errors at baseline. This result has important implications for the mechanisms that cause the prisms to create aftereffects.

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Visuomotor Learning

Visuomotor learning is the process of using vision to perform motor tasks when a particular movement in the body is dependent on information from the visual system (Bedford, 1993). An example of this process is reaching for an object where people first locate the item through vision and reach out to touch it by hand after they focus on it. They are then able to reach for it accurately, performing the motor task, because it has been located in their field of vision. The motor and visual systems are aligned, allowing for accurate reaching. If these systems did not match, then people would experience misalignment, where they would reach for something and miss it because of the misalignment between the motor and visual systems. Visual target locations are thus transformed into a motor performance, as the two systems are coordinated.

In order to accomplish a task involving visuomotor learning, it is necessary to combine extrinsic coordinates from the environment, which are processed through eyesight, with internal or intrinsic coordinates. The intrinsic coordinates refer to the feedback originating from the person's body, such as the location or posture of the limb. This process of combining the spatial information derived from the person's environment and the internal postural information is called *coordinate transformation* (Redding and Wallace, 1996). Reaching to visually defined targets involves translating the visual information that is received initially in the eye into a motor plan, one that specifies the sequence of postural changes that are required to bring the hand to the target (Jackson et al., 2009; Fernández-Ruiz, Hall, Vergara, and Diaz, 2000; Bedford, 1993).

As these transformations become more complex, more steps may be required to transform coordinates, such as those along the length of the shoulder to the hand. A sensorimotor task of this complexity requires coding hand position, and transforming the coordinates into elbow and shoulder-centric space (Redding and Wallace, 1997). Motor commands in this example have to be transformed from a movement path representation to a muscle force representation along the arm, from the hand to the shoulder. Muscle force, or contraction, is required to make the movement happen in the person's arm, with the need for increasing commands as the movement becomes more complex. The individuals' sense of their limbs and posture and their respective location in relation to their bodies are dependent on proprioceptive and visual cues.

Prism Adaptation for Studying Visuomotor Learning

Years of visuomotor experience results in a well-learned coordinate transformation for converting visual coordinates into proprioceptive coordinates. However, brain injury and normal growth processes can disrupt this well-learned transformation, leading to misalignment. The prism adaptation paradigm has exceptional advantages for the study of visuomotor learning because it creates a misalignment of known magnitude between the visual and action systems. It is a much more precise way of studying alignment than other means that may cause misalignment, like some sort of physiological change in the brain (Redding and Wallace, 1997). A transformation caused by prisms is a known, quantifiable disturbance of system input.

The prism adaptation paradigm is comprised of three main steps: pre-exposure baseline measurement of performance, active exposure to the prismatic displacement, and post-exposure measurement of adaptation persistence called an aftereffect (Redding et al., 2005). When participants put on laterally-displacing prisms and reach for something, they initially miss it, reaching too far in the direction of the prisms they are wearing. For example, if the participants are wearing right-deviating prisms, they will reach to the right of the target. After a few more attempts, the participants correct their movements and reach the object they are aiming for. This is termed the adaptation process (Choe, 1974; Fernández-Ruiz et al., 2000). Experimenters can determine if adaptation, which is a form of learning, has occurred by examining the aftereffects once the prisms have been removed. After the prisms have been removed, participants typically make movement errors in the direction opposite of the prism displacement.

Pointing to targets is a common task used in prism adaptation. The training task is usually performed with full sensory feedback and knowledge of results. This is done in order to enable adaptation to the prismatic distortion. As will be explained below, the production of error is crucial to the adaptation process, so the participant's action system can recognize that an error is being made, though the participant need not be aware of it. The pre- and post-exposure tasks are performed without sensory distortion, as the goggles have been removed, and without sensory feedback. The change in performance in the pre-and post-exposure tasks is the aftereffect. This is a measure of transfer of prism adaptation when feedback and knowledge of results are no longer available (Redding and Wallace, 1997). Once the prisms are removed, the participant will often overcorrect, reaching too far in the opposite direction. This negative aftereffect can be caused by a shift in felt limb position. Differing responses on the participant's pre- and post-adaptation tests indicate this adaptive shift (Harris, 1965). These aftereffects are well established as quantitative measures of adaptation (Redding and Wallace, 1992; Michel et al., 2003).

Different Means of Reducing Error During Prism Adaptation

During prism adaptation, participants may reduce their movement error through explicit, strategic processes or through more implicit, automatic realignment processes. *Recalibration* refers to the error-reduction that occurs via strategic perceptual-motor control processes (Redding and Wallace, 1996). It is used to enable rapid adaptive behavior during prism exposure. For example, if participants realize that when they point they end up several inches to the right of the target, they may decide to aim several inches to the left of the target in order to point more accurately on the next trial. Recalibration may also occur when participants consciously use online visual information to correct the trajectory of their hand-paths mid-movement (Redding and Wallace, 1993).

The second means of reducing error during prism adaptation is via *realignment* of the perceptual and motor coordinates. Realignment is thought to be an implicit, automatic response to a misalignment of the perceptual and motor coordinates. Because misalignment is necessary for realignment to occur, the implicit realignment of perceptual and motor coordinates can actually be impeded by recalibration. That is, if a person strategically adopts a new movement goal to which he accurately points, there will be no misalignment for the perception and action systems to detect. Thus, there will be little learning or change in the coordinate systems (Fernández-Ruiz et al., 2000). Furthermore, because recalibration is more of a strategic control type of learning, rather than a global change in coordinate systems, pre-post shifts of performance are only demonstrated on tasks very similar to the training task: broad generalization across tasks is not observed. However, visual and proprioceptive aftereffects (described below) are typically still observed (Bedford, 1993; Redding and Wallace, 2006).

The exact coordinates that are changed or realigned in response to misalignment can vary, with changes produced in visual coordinates or in proprioceptive coordinates (Harris, 1965; Redding and Wallace, 1990). In visual realignment, the felt position of the eyes is adjusted relative to the head. Visual realignment can be detected by asking participants to inform the experimenter when they believe a moving visual target has arrived in the center of their view. Any directional change in the accuracy of these judgments from pre- to post-prism adaptation would reflect visual shift. In proprioceptive realignment, the felt position of the moving limb relative to the head is adjusted. Proprioceptive realignment can be detected by asking participants whose eyes are closed to point straight ahead of their body's midpoint. Typically, participants' pre- and post-proprioceptive pointing performance will shift in the direction opposite of the prism displacement (Redding and Wallace, 1996). The extent of proprioceptive shift is greater for exposure tasks that encourage the use of visual information to guide the limb while wearing the prisms. The extent of visual shift is greater for exposure tasks that encourage the use of proprioceptive information from the limb to guide eye movement (Redding and Wallace, 1990, 1996).

Furthermore, it has been found that visual and proprioceptive realignment depend critically on blocking participants' view of the initial portion of their hand-path. When the hand's starting position is visible, visual and proprioceptive aftereffects are minimal (Redding and Wallace, 1996). This result suggests that during the task, the participants are engaged in recalibration, which interferes with the realignment effects. If the hand is visible during a pointing task, the participant can quickly change his route if he sees that he is pointing too far in one direction due to the prism goggles. As mentioned above, realignment depends on misaligned sensorimotor systems so that spatial discordance can be detected (Redding and Wallace, 1993).

Thus, error production during prism adaptation is crucial for the emergence of a *realignment* of visual and motor coordinates. If the participant is not allowed to make any errors, the level of adaptation will be diminished. The participant's visuomotor system must detect a discordance to be able to correct for it on future trials. Findings demonstrate that when the experimenter moves the participant's arm in a pointing task, this passive movement does not provide the same magnitude of adaptation as an active task, in which participants move their own arms (Welch, Choe, and Heinrich, 1979; Baily, 1972). By not allowing the participant to make any errors, the experimenter prevents the misalignment between the perception and action systems.

Preventing participants from seeing errors immediately after they make them will also affect the adaptation process. By creating a delay between when the participants point and when they are able to see the outcome, experimenters are able to decrease the amount of adaptation that occurs. Even a delay of 50 milliseconds will reduce the amount of prism adaptation, as determined by smaller aftereffects, when compared to no delay (Kitazawa, Kohno, and Uka, 1995).

Transfer of Prism Adaptation is Task Dependent

The aftereffects, which measure adaptation once the prism goggles have been removed, are more likely to transfer if the adaptation task is similar to the exposure task, especially if participants learned via recalibration, a method of strategically correcting errors (i.e., strategically; Bedford, 1993; Redding and Wallace, 2003). An example of this is when the same target-pointing task is used for both training and testing; that is, for adaptation and pre- and post-exposure tasks. Post-exposure transfer occurs in the form of performance opposite the direction of prismatic displacement. If recalibration is deployed to reduce performance error during exposure, transfer will be most easily observable for test targets that have the same spatial location relative to the participant as training targets and will deteriorate for test locations that are incrementally different from training target locations (Redding and Wallace, 2006).

While recalibration generalization depends on similarity of the tasks performed while wearing prisms, realignment generalization depends on the involved spatial maps and proprioceptive cues. Realignment will generalize to any task that implicates the realigned coordinates exercised during prism exposure of the participant either separately or in combination with other sensorimotor systems. This is because realignment is localized in the transformation that links a sensorimotor system to all other sensorimotor systems (Redding and Wallace, 2002). An example of this is adaptation to a target-pointing exposure task with prismatic displacement, which usually involves a change in origin alignment of the coordinate frames for both the visual and proprioceptive sensorimotor systems. Such realignment contributes to a reduction in the direct effects of prismatic displacement. After exposure, realignment produces changes in target pointing in the opposite direction of the prismatic displacement, in the same direction as recalibration. These aftereffects will extend equally to all locations in the realigned visual proprioceptive coordinates. The coordinates will realign as the person corrects the position of the limb in the pointing task, based on experience from previous trials. It is therefore possible to transfer realignment, as long as the task implicates the realigned coordinates that were exercised during the prism exposure task.

There is evidence that transfer can occur, as a result of realignment generalization, with tasks that are not the same, and which may or may not implicate the same coordinate systems. In their 2004 experiment, Girardi et al. found that adapting participants on a pointing task transferred to a haptic circle task, one in which they explored the circle by touch. While blindfolded during the pretest, participants were asked to make one full exploration of the circumference of a circle that was placed before them. The participants were then asked to point to twenty dots as their prism adaptation procedure. Afterwards, they performed visual, proprioceptive, and visual-proprioceptive aftereffects tasks, followed by the haptic circle task again. They found that a rightward lateral shift of performance was induced by adaptation to left-shifting prisms, indicating a negative aftereffect, but the left prisms did not show any significant transfer effects to the haptic exploration task (Girardi et al., 2004).

Transfer effects are even seen from one limb to another. In the 2007 study by Michel et al., pre- and post-tests were comprised of visual and auditory open-loop pointing tasks, which required the participant to point in vertical alignment with a single central LED or a loud speaker on the lower level of the box. The adaptation procedure was performed with the right hand only. In the pre- and post-tests, the left unexposed hand and right exposed hands were used successively with twelve trials, each in visual and auditory pointing tasks. This was done in order to assess the level of intermanual transfer adaptation, from one hand to the other. They had two groups of participants: one received a 10° rightward shift and the other received different prisms, unbeknownst to them, starting at 2° and ending at 10° (i.e., multiple-step group). Findings showed that a significant transfer occurred to the non-exposed hand in the multiple-step group (Michel et al., 2007). The multiple-step group also showed no awareness of the prism displacement, which suggests that they likely experienced realignment rather than strategic recalibration. Thus, this study is consistent with the prediction of broader generalization with realignment than with strategic recalibration.

Transfer of Prism Adaptation Depends on Direction of Shift

Recently, some have claimed that adapting healthy young individuals to left-shifting prisms produces behavior similar to that observed in left-neglect patients (Colent, Pisella, Bernieri, Rode, and Rossetti, 2000; Michel, 2006). Left neglect occurs after right brain injury and is characterized by a failure to respond, orient, or initiate action towards contralesional stimuli (Heilman, Watson, and Valenstein, 2003). The idea that prisms produce a neglect-like syndrome in the healthy young relies on the dissociation in the aftereffects observed with left and right-shifting prisms. Some researchers have observed that both left and right prisms show aftereffects on tests of visual and proprioceptive shift, but only left-shifting prisms induce rightward aftereffects across a broader range of tasks (Michel, 2003). This dissociation was first observed in line bisection tasks where a rightward bias after adaptation was observed (Colent et al., 2000). In this instance, the participants adapted to leftward prisms and displayed rightward aftereffects once they were removed.

The sensorimotor effects produced by prism adaptation cannot fully explain the bias observed in a perceptual bisection task. One study showed a bias in the estimation of the line center in space at a distance from the participant. It was shown that bisection judgments shifted significantly to the right following adaptation to left-deviating prisms. Adaptation to rightward-deviating prisms did not induce a corresponding leftward bias (Berberovic and Mattingley, 2003).

There are several characteristics of neglect that are also found in normals following prism adaptation. Several authors have argued that prism adaptation to the right does not produce generalizable aftereffects in normals, despite the production of sensorimotor aftereffects of the same magnitude whether prisms are rightward or leftward shifting (Colent et al., 2000; Redding and Wallace, 2006). An example of this phenomenon is the previously mentioned Girardi et al. experiment (2004). There was a rightward bias in the estimation of the center of the haptically explored circle that was in peripersonal space, immediately surrounding the participant.

Should Prism Adaptation While Walking Generalize to Other Tasks?

Walking while wearing prism goggles might be more difficult to control experimentally, but it has greater practical and ecological validity. It also prompts the greater articulation of theory necessary to identify relevant variables, as it is a particularly useful demonstration of how visuomotor learning works (Redding and Wallace, 1985). Prism adaptation during whole body movements may involve sensorimotor realignment of a different brain region or multiple brain regions, as compared to simpler tasks, like dot pointing (Morton and Bastian, 2004). It is possible that prism adaptation during whole body movements involves a general system for visuomotor remapping, which involves realignment of higher-order brain regions that may show better transfer to lower-level effector-specific coordinate systems.

Early studies in walking during prism exposure found a higher level of visual shift for leftward-deviating prisms than right ones (Redding and Wallace, 1976, 1988). The visual shift was observed in a task in which the participant was asked to judge when a target was directly in front of his nose. They also found that proprioceptive shift was observable with both left and right prisms as long as the participant was able to feel the wall, providing proprioceptive clues. In general, compared to visual shift, proprioceptive shift was greater during walking exposure than during a task involving active hand exposure, such as pointing.

Several studies have been conducted using walking while wearing prism goggles as an adaptation task and have had varying results regarding this adaptation's ability to transfer to other tasks. In the 2004 study by Morton and Bastian, the generalizability of reaching versus walking prism adaptations was compared. Two groups of participants were involved. One group adapted to prisms while walking and was then tested on reaching. The other group adapted to prisms while reaching and was then tested on walking. Participants wore prisms that displaced their vision approximately 17° to the right. For the reaching task, participants stood facing a rectangular panel and made single movements with the index finger towards a target on the panel. The walking task required participants to walk, within boundary lines marked on the floor, with arms across their chest (Morton and Bastian, 2004).

Morton and Bastian found that, while wearing the prisms, all participants showed an initial rightward deviation in their reaching endpoint or walking endpoint. This improved after successive trials. When the prisms were removed, all participants showed a negative aftereffect, which caused them to deviate in the direction opposite of the prisms they were wearing. Only the group that adapted to walking showed generalization to reaching. The group that adapted to reaching did not generalize to walking. Visuomotor adaptation can therefore be highly general or highly specific, depending on the type of movement. This marked asymmetry shows how important the tasks are and raises the question of why adaptation might occur on some tasks and not others (Morton and Bastian, 2004).

Another study using walking as an adaptation task had very different results. In their 2008 study, Michel et al. conducted two experiments with two different adaptation tasks. In the first experiment, participants performed manual pointing pre- and post-tests with left or right deviating prisms and adapted using either manual or locomotor tasks. The second experiment was almost identical except that the pre- and post-tests were goal-oriented locomotor tasks. For the manual pointing task, participants held their right hand at sternum level, looked briefly at the central target, closed their eyes, and then immediately pointed to where they believed the target to be. For the goal-oriented locomotor task, participants stood upright at the starting position and looked at a visual target placed 7m in front of them. They were then blindfolded and walked up to where they believed the target to be. Locomotor adaptation involved participants walking along a white rectangle drawn on the floor for twelve minutes. They walked naturally and looked two to three steps ahead. For the manual adaptation task, participants engaged in visuo-manual pointing for twelve minutes with their left or right arm. The prisms induced a lateral displacement of 11.4° (Michel et al., 2008).

The findings indicated that pointing adaptation produced aftereffects in manual pointing. These aftereffects were symmetric after adaptation to a leftward or rightward optical deviation. Locomotor adaptation produced symmetrical locomotor aftereffects but these aftereffects did not transfer to pointing. Pointing adaptation produced locomotor aftereffects only following adaptation to a leftward optical deviation (Michel et al., 2008). Given that only leftward-deviating prisms have been found to produce neglect-like behavior in normal subjects, these findings are rather interesting. A possible explanation is that a combination of higher-order spatial remapping and sensorimotor aftereffects is created following leftward-deviating adaptation.

Why might two experiments, both using locomotor adaptation tasks, have arrived at such different results? Morton and Bastian (2004) had participants walk on a straight walkway, but Michel et al. (2008) had participants walk in a relatively small border of a rectangle. Although Morton and Bastian measured and reported the walking error produced by participants in their study (and their participants did err, walking outside the boundaries of the walkway), Michel et al. did not. It is therefore possible that the walking task used by Michel et al. did not allow participants to produce error while walking – thus producing more recalibration rather than realignment -- and this may account for the difference between the two studies. Participants were also instructed to walk in different ways. While Morton and Bastian had participants walk with their arms across their chests, Michel et al. asked participants to walk as they would naturally. By requesting that participants walk with their hands across their chests, the experimenters are removing proprioceptive clues from the participants, which can have an effect on their adaptation.

The Present Experiment

The present experiment examined whether the different results of the Morton and Bastian (2004) and Michel et al. (2008) studies are due to differences in the production of error during an adaptation task involving walking. Basing the experiment on the Morton and Bastian and Michel et al. paradigms, participants walked on a 12'8" walkway. The instructions given to participants were manipulated: half were required to walk the pathway in an error-free manner. They were alerted every time they stepped outside of the boundaries. The other half of the participants were allowed to produce errors while walking with the prisms. It was expected that the error-free condition would be conducive to recalibration rather than realignment, and thus, generalization of the adaptation to a pointing task in this group was not expected (Michel et al., 2007, 2008; Redding and Wallace, 1985). The natural walking group, however, should adapt via realignment and thus, we expected generalization from the walking task to a target-pointing task.

We measured, at several different locations throughout their walk-path, where the participants were in relation to the middle of the walkway. Though Morton and Bastian only used rightward prisms, we used both right-and leftward ones, similar to Michel and colleagues. Since Michel et al. found transfer effects with rightward-deviating prisms, it was predicted that they would exist for leftward-deviating prisms as well in the group that was allowed to produce error in their walking during prism adaptation.

Methods

Participants

One hundred and six right-handed undergraduates (69 female, 37 male) at a Catholic university in the Northeast participated in the study for course credit. Only participants who were right-handed, had the ability to walk, and scored in the normal range (12 or lower) on the Vertigo Symptom Scale-Short Form (Wilhelmsen, Strand, Nordhal, Eide, and Ljunggren, 2008; see Appendix A) were allowed to participate.

Design

The primary design of the experiment was a 2x2 between subjects factorial. There were two independent variables. The first was the type of prism: participants wore either rightward or leftward prisms that displaced their vision 14° laterally. The second independent variable was adaptation instructions. The ability of the participant to produce errors was manipulated. One group, the error-free group, was instructed to walk in a straight line as much as possible and was informed anytime they stepped outside the walkway. The second group was allowed to walk naturally. The dependent variable was the difference between performance on pre-and post-tests of walking, target-pointing, and visual and proprioceptive shift.

Procedure

There were two experimenters with each participant. The experimenters worked together, presenting stimuli and recording the participants' performance during the pointing/reaching tasks. During the goal-oriented locomotor task, which involved walking to a target, one experimenter monitored the participant's walking while the other alerted the error-free group to their deviations. Participants were tested one at a time.

After reading and signing the informed consent form, participants were screened for susceptibility to vertigo using the Vertigo-Symptom Scale-Short Form (Wilhelmsen, et al., 2008; see Appendix A). The scale asked participants to think about how often they had experienced several feelings in the last month that could indicate vertigo- for example, nausea and dizziness. The creators of the scale have validated a cutoff of higher than 12 as indicative of susceptibility to vertigo. Anyone who scored above a twelve (9 participants) was excluded.

Prism adaptation was assessed by first asking participants to complete a series of pre-test/baseline tasks, then having them adapt to either left-shifting or right-shifting prisms while walking. After prism adaptation (post-test) the participants performed the same set of tasks they performed at pre-test.

Pre/Post Tests

All pre-test and post-test measures were taken while the participant was *not* wearing prisms. All pre and post-tests were performed in the following order: target-pointing, visual shift, proprioceptive shift, and walking. The target-pointing task was performed first so as to maximize the chance of observing generalization to that task while minimizing the chance that participants de-adapted while performing the other post-tests.

Target-Pointing. For the target-pointing test, participants sat in front of a computer and made pointing movements to dots appearing one at a time on a touch-screen monitor. All pointing movements were made under an occluding shelf that blocked participants' view of the initial portion of their handpath, but allowed participants view of the terminal portion of their handpath. For each of three trials, a single black dot appeared on a white background. Once the participant pointed to the dot by touching the monitor, it was replaced by a random-dot visual mask. After a 500ms delay, another dot appeared. The amount of lateral displacement of participants' pointing was measured. The computer recorded the responses of participants in pixels for the target-pointing task. The pixels were then converted to millimeters and the error was calculated by taking the difference between the middle of the target dot and the location of the participants' pointing.

Visual Shift. For the visual shift test, participants were seated at a table opposite the experimenter. On each of three trials, the experimenter moved a visual target (i.e., a pen) across the top of a board and the participant said "stop" when he believed the pen to be directly in the center of the board. This was done twice starting from the participants' right and once from their left, alternating between trials. Measurements on the side of the board facing the experimenter in centimeter increments allowed the experimenter to measure how far from the center the pen was when the participant said "stop."

Proprioceptive Shift. For the proprioceptive shift test participants were seated at a table opposite the experimenter. On each of three trials, they were asked to close their eyes and to place their right fist at the center of their chest and then use their index finger to point to where they thought was straight ahead of their body's midline. The experimenter used a clear, Plexiglas board, centered on the participant's midline to identify and record the participant's lateral deviation from center by looking at the centimeter increments written on the board.

Walking. For the walking pre- and post-test, on each of three trials, participants started with their toes aligned with a piece of black electrical tape and were asked to walk to a 4 inch black circle appearing 12'8" away on the wall opposite their location. They were asked to walk naturally, and to look straight ahead rather than looking down at their feet. Three video cameras mounted on the ceiling recorded the initial, middle and terminal portions of the participant's walking path. Each video camera captured approximately three feet of the entire walking path.

Adaptation

During adaptation, participants donned either the left or right-shifting prisms, which displaced participant's vision by 14° laterally. All participants performed 25 walking trials while wearing the prisms. Participants adapted to the prisms while walking in one of two conditions: natural or error-free. In the natural walking condition, participants performed the walking exactly as described for the walking pre-test measure. Participants in the error-free condition also walked to the 4 inch black circle target on the wall opposite their starting point, but they were asked to walk in as straight a line as possible, while maintaining visual focus on the target. For this condition, a 2' wide walking path was projected along the floor using laser straight edges of the kind used for leveling in construction. Participants in the error-free condition were instructed to stay within the bounds of the path. Every time they exited the bounds of the path, the experimenter triggered a sound from a keyboard indicating which way had had exited the path. A high tone indicated that they had exited to the right of the path and needed to step towards the left in order to stay within the boundaries. A low tone indicated that they had exited to the left of the path and needed to step towards the right in order to stay within the boundaries. While correcting their movement, they were instructed to continue looking ahead at the target and not down at their feet.

Coding of Walking Error

Participants' walking error was coded after data collection by placing a piece of tracing paper over a computer screen. The participant's walking path was traced onto the paper. This was done separately for the early, middle, and terminal portions of the walking path. The length of the participant's walking path (in mm) and the direction of deviation from center (left as negative, right as positive) was then calculated from the paper tracing. The difference was then taken between the length of the participant's lines and a straight line, which measured 211 mm. Since the shortest distance between two points would be a straight line, any deviation from the straight line would indicate walking errors. The longer the participant's path, the greater the deviation from a straight line to the target stimulus. Because the total deviation from the early, middle, and terminal portions of the path should sum to zero if the participant walked in a straight line, the directional errors for the three portions of the walking path were summed.

Results

For all tasks, the median of the three pre-test trials served as the measure of pre-test performance. Similarly, the median of the three post-test trials as the measure of post-test performance was used. Adaptation to the prism goggles during the walking task was assessed by comparing early walking error (median of the first three walking trials) to late walking error (median of the last three walking trials).

Baseline

Tables 1 and 2 depict the baseline error performance of participants on the four pre-test tasks. Single-sample t tests of the average error performance (see bottom row of each table) were conducted against zero for each measure at baseline in order to determine any baseline biases that might exist for the participants. As can be seen in the Tables, all groups showed a rightward bias at baseline, though only the visual shift (M= .43, SD= 1.52) and target-pointing tasks (M= 4.10, SD= 8.68) were significantly different from zero, $t(102)$= 2.93, p= .004 for the visual-shift and $t(102)$= 4.87, p< .01, for the target-pointing task.

To evaluate whether there were any differences in the baseline performance of participants in the four conditions, separate 2 x 2 ANOVAS were conducted with prism (left, right) and adaptation condition (natural, error-free) as factors. The baseline performance for all tasks was not significantly different between the directions of prism goggle or condition, all Fs < 3.049, ps >.084[1].

Table 1

Errors at Baseline on the Visual and Proprioceptive Shift Tests

	Visual Shift	Proprioceptive Shift
Right Prism		
Error-free	.42 (1.63)	1.31 (5.07)
Natural	.73 (1.64)	.62 (3.62)
Right Average	.54 (1.49)	.83 (4.07)
Left Prism		
Error-free	.64 (1.37)	.39 (2.89)
Natural	-.08 (1.41)	-.08 (3.94)
Left Average	.33 (1.57)	.27 (3.76)
Total Average Error	.43 (1.52)	.56 (3.92)

Note. Means and standard deviations (in parentheses) in mm for the errors at baseline on the visual and proprioceptive shift tests. Negative numbers indicate leftward errors and positive numbers indicate rightwards errors.

Table 2

Errors at Baseline on the Walking and Target-Pointing Tasks

	Walking	Target-Pointing
Right Prism		
Error-Free	.93 (18.93)	3.31 (8.19)
Natural	.18 (17.53)	4.75 (8.520)
Right Average	.54 (18.05)	4.06 (8.27)
Left Prism		
Error-Free	2.58 (15.20)	4.42 (9.17)
Natural	6.04 (15.93)	3.89 (9.340)
Left Average	4.31 (15.52)	4.15 (9.17)
Total Average Error	2.39 (16.88)	4.10 (8.68)

Note. Means and standard deviations (in parentheses) in mm for the errors at baseline on the walking and target-pointing tasks.

Adaptation

Table 3 depicts the walking error during adaptation as a function of instruction condition and prism. As can be seen in Table 3, participants wearing right goggles erred more towards the right and participants wearing left goggles erred more towards the left. This was true for both early and late adaptation trials. Participants wearing right and left goggles performed more errors in the early than late adaptation trials. These impressions were confirmed by the analysis.

Table 3

Errors on the Early and Late Adaptation Trials

		Early Adaptation	Late Adaptation
Right			
	Error-Free	70.88 (14.24)	32.88 (17.48)
	Natural	67.82 (11.21)	31.64 (21.09)
	Total	69.30 (12.73)	32.24 (19.26)
Left			
	Error-Free	-67.96 (10.41)	-37.38 (13.39)
	Natural	-63.08 (12.60)	-37.00 (12.23)
	Total	-65.52 (11.71)	-37.19 (12.70)

Note. Mean participant errors on the early and late adaptation trials. Standard deviations are in parentheses.

A 2 x 2 x 2 ANOVA with prism (left, right) adaptation condition (natural, error-free) and trial (early, late) as factors was conducted to investigate error differences between early and late adaptation trials. There was a main effect of trial for early versus late adaptation, $F(1,102) = 7.28, p = .008, \eta_p^2 = .07$, and a main effect of prism goggle, $F(1,102) = 1960.01, p < .001, \eta_p^2 = .95$. There was also a significant prism by early versus late interaction, $F(1,102) = 405.49, p < .01, \eta_p^2 = .80$. This interaction is depicted in Figure 1. For both left, $F(1,102) = 149.35, p < .001, \eta_p^2 = .59$, and right, $F(1,102) = 265.53, p < .001, \eta_p^2 = .72$, goggles participants significantly improved from the early to late adaptation trials. They made fewer errors in the later trials than the early ones.

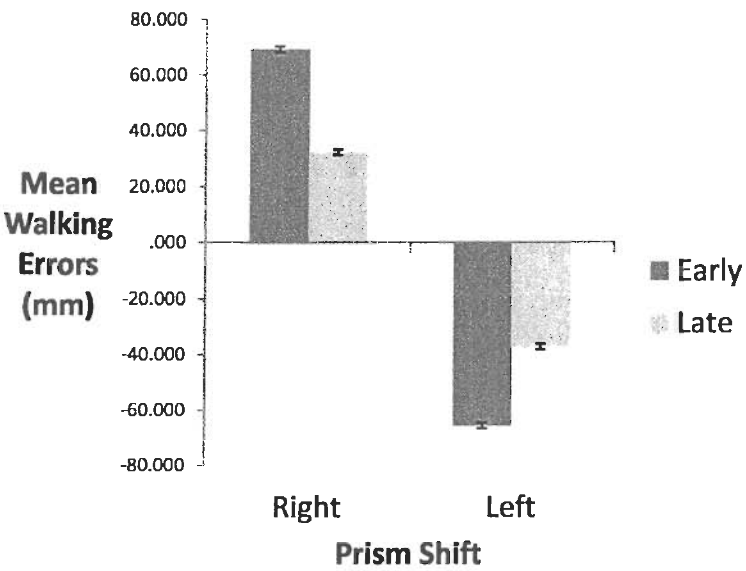


Figure 1. Mean participant errors on early and late adaptation trials in mm for left and right prisms. Error bars are ± 1 SE.

The predicted results of fewer errors for the error-free condition compared to the natural condition were not seen. As can be seen in Table 3, participants made similar magnitude of errors while walking with the prisms, regardless of the instruction condition.

Baseline Vs. Post-Test

The post-test measures were calculated in the exact same manner as baseline. Because other researchers have found differences in the ability of the right and left-shifting prisms to produce aftereffects, in addition to performing the 2 x 2 x 2 ANOVA with prism (left, right), adaptation condition (natural, error-free), and pre/post as factors, for each of the measures, planned comparisons were used, assessing the effect of baseline/post-test at each level of prism to determine the specific effect of the left and right prisms.

Visual Shift Test. Participants' performance on the pre and post visual and proprioceptive shift tests appears in Table 4. In comparing the performance errors of participants in the baseline and post-visual shift test, it was found that participants performed more errors on the post-test compared with baseline. On average, participants' errors moved more towards the right at post-test. There was a main effect of baseline versus post-test, $F(1,102) = 5.44$, $p = .022$, $\eta_p^2 = .05$. There was no effect of condition and no significant interactions. In order to examine the effects of the prism shift, the simple main effects of pre/post for each prism shift were looked at separately. There was a main effect of baseline versus post-test for the left goggles only, $F(1,102) = 6.57$, $p = .012$, $\eta_p^2 = .06$, with $M = .33$, $SD = .21$ at baseline and $M = .87$, $SD = .21$ at post-test. After adapting to the left prisms, participants' visual estimation of center was shifted rightward, indicating a negative aftereffect.

Table 4

Baseline and Post-Test errors on the Visual and Proprioceptive Shift Tests

	Visual Shift		Proprioceptive Shift	
	Baseline	Post-Test	Baseline	Post-Test
Right				
Error-Free	.42 (1.63)	.58 (1.33)	1.31 (5.07)	1.81 (5.34)
Natural	.64 (1.37)	.79 (1.50)	.39 (2.88)	.00 (4.22)
Total	.54 (1.49)	.69 (1.41)	.83 (4.07)	.87 (4.83)
Left				
Error-Free	.73 (1.64)	1.00 (1.47)	.62 (3.62)	2.85 (5.02)
Natural	-.08 (1.41)	.73 (1.82)	-.08 (3.94)	.38 (3.38)
Total	.33 (1.57)	.87 (1.65)	.27 (3.76)	1.62 (4.42)
Total Error	.43 (1.52)	.77 (1.53)	.56 (3.92)	1.24 (4.63)

Note. Average baseline and post-test errors in mm for the visual and proprioceptive shift tests. Standard deviations are in parentheses.

Proprioceptive Shift Test. On average, participants made more errors on the post-test than the baseline measure of proprioceptive shift (Table 4). These errors were more rightward in the post-test, though the pre-post main effect did not reach significance[2], $F(1,102) = 3.04, p = .084,\ \eta_p^2 = .03$. There was a main effect of instruction condition, $F(1,102) = 4.13, p = .045,\ \eta_p^2 = .04$, with $M = 1.64$, $SD = .52$ for the error-free condition and $M = .18$, $SD = .51$ for the natural condition. There was no main effect of prism or prism by condition interaction. Following up with simple main effects tests for the prism goggles by pre/post-test, there was a significant main effect of baseline versus post-test for the left goggles only, $F(1,102) = 5.52, p = .021,\ \eta_p^2 = .05$, with $M = .27$, $SD = .55$ for baseline and $M = 1.62$, $SD = .63$ in the post-test. This indicates a negative aftereffect, as those who wore left goggles, on average, performed errors that were more towards the right in proprioceptive shift post-test. For the right prism goggles, the baseline performance for the proprioceptive shift test ($M = .85$, $SD = .54$) was not significantly different from the post-test performance for the proprioceptive shift test ($M = .90$, $SD = .62$), $F(1,102) = .01, p = .924,\ \eta_p^2 = .00$. This pattern is similar to the results of the previously described visual shift test, which also showed a negative aftereffect for the left goggles only.

Target-Pointing. Participants' performance on the baseline and post target-pointing and walking tasks appears in Table 5. In comparing the errors of participants in baseline and post-test target-pointing performance, it was found that participants performed more errors at baseline than on the post-test. Participants were right-biased at baseline and, on average, made more leftward errors at post-test (Table 5). There was a main effect of baseline/post-test, $F(1,102) = 5.36, p = .023,\ \eta_p^2 = .05$, and no main effect of condition or interactions. In examining the simple main effects of pre/post for each prism goggle, it was found that the left goggles had a significant effect of baseline versus post-test performance, $F(1,102) = 5.44, p = .022, \eta_p^2 = .05$, with $M = 4.15$, $SD = 1.22$ at baseline and $M = -2.89$, $SD = 2.68$ at post-test. This main effect did not exist for the right goggles, $F(1,102) = .86, p = .356, \eta_p^2 = .01$, with $M = 4.03$, $SD = 1.20$ at baseline and $M = 1.28$, $SD = 2.63$ at post-test (see Figure 2).

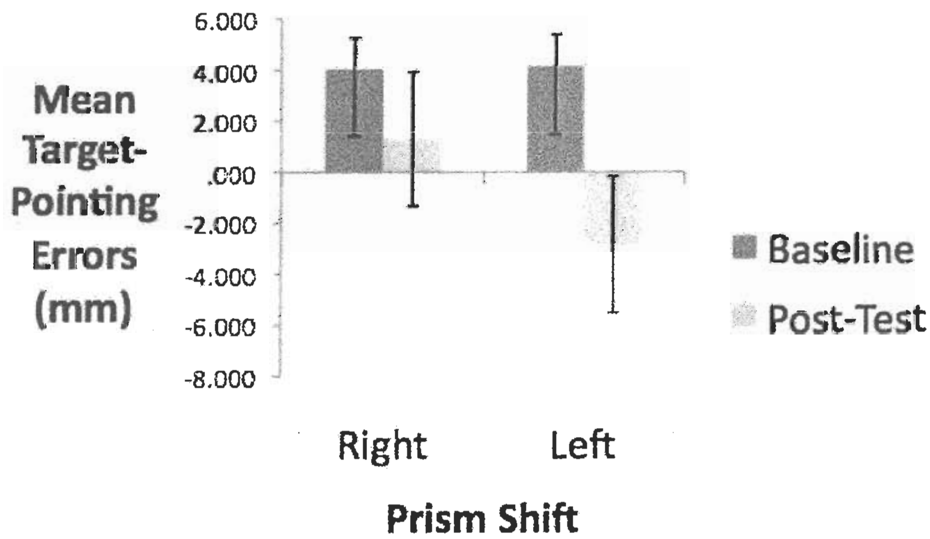


Figure 2. Baseline and post-test target-pointing errors in mm for left and right prism goggles. Error bars = 1 SE

Table 5

Baseline and Post-Test Errors on the Walking and Target-Pointing Tasks

	Walking		Target-Pointing	
	Baseline	Post-Test	Baseline	Post-Test
Right				
Error-Free	.92 (18.93)	-.08 (22.30)	3.31 (8.12)	2.31 (18.84)
Natural	.18 (17.53)	-.04 (23.05)	4.75 (8.51)	.25 (17.32)
Total	.54 (18.05)	-.06 (22.48)	4.06 (8.27)	1.24 (17.93)
Left				
Error-Free	2.58 (15.20)	-2.35 (22.44)	4.42 (9.17)	-2.31 (21.92)
Natural	6.04 (15.93)	-2.54 (25.03)	3.89 (9.34)	-3.46 (18.97)
Total	4.31 (15.52)	-2.44 (23.54)	4.15 (9.17)	-2.88 (20.31)
Total Error	2.39 (16.88)	-1.23 (22.92)	4.10 (8.68)	-.78 (19.15)

Note. Average baseline and post-test errors in mm for the walking and target-pointing tasks. Standard deviations are in parentheses.

Walking Trials. Similar to the performance on the dot-pointing task, participants wearing both right and left prisms erred more to the left at post-test than at baseline, though this effect only reached significance for the left goggles These means are depicted in Figure 3 and in Table 5. The 2x2x2 ANOVA revealed no main effect of baseline/post-test or prismatic shift. There was also no interaction. Simple main effects tests of pre/post were performed at each level of prism. For the left goggles, participants' erred more towards the left at post-test, $F(1,102) = 4.53, p = .036, \eta_p^2 = .04$. For the left goggles $M = 4.31$, $SD = 2.35$ at baseline and $M = -2.44$, $SD = 3.22$ at post-test. For the right goggles $M = .55$, $SD = 2.31$ at baseline and $M = -.06$, $SD = 3.16$ at post-test, $F(1,102) = .04, p = .846, \eta_p^2 = .00$.

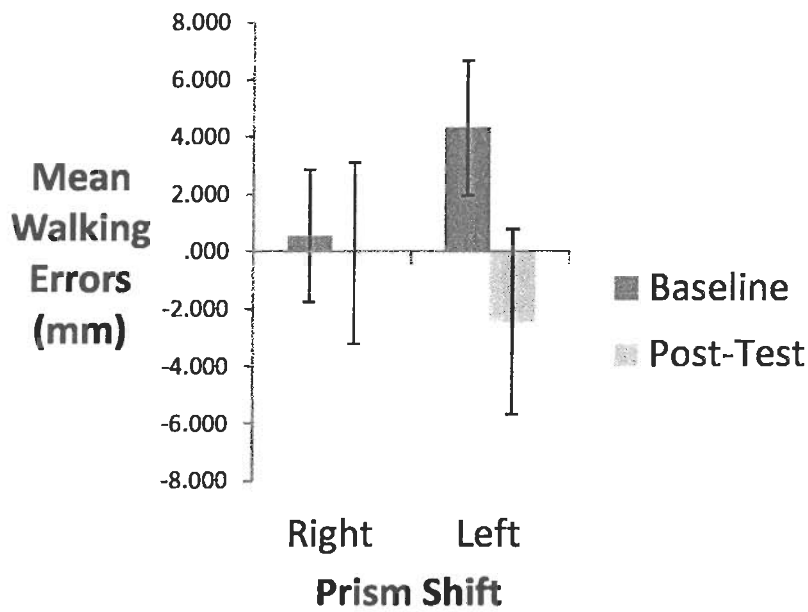


Figure 3. Baseline and post-test walking errors in mm for left and right prism goggles. Error bars = 1 SE

Table 6.

Summary of Results: Pre/Post Shift

	Left Goggles	Right Goggles
Visual Shift	Significant Right	Not Significant Right
Proprioceptive Shift	Significant Right	Not Significant Right
Target-Pointing	Significant Left	Not Significant Left
Walking	Significant Left	Not Significant Left

Note. This table shows the direction of shift in errors from pre- to post-test, separated by difference in prismatic shift.

Analysis of Individual Differences

Because pre-post differences in performance may vary with the magnitude of participants' adaptation while wearing prisms, individual differences were analyzed using correlations in order to determine if participants' level of adaptation at the end of the adaptation trials was correlated with the amount of generalization that was seen in the target-pointing and walking post-tests. This was done by analyzing correlations between the difference in pre- and post-test and the errors made during the late adaptation trials.

This difference score was calculated by subtracting the median pretest errors from the median post-test errors. Negative numbers indicate leftward errors and positive numbers indicate rightward errors.

Target-Pointing. The magnitude of the difference score in target-pointing was assessed in relation to the magnitude of errors performed at the end of the adaptation trials. Figure 4 depicts a scatterplot of error during the late walking trials and the difference in pre-post target pointing performance for participants who adapted to right goggles. Three outliers, which can be seen in the upper left corner of the scatterplot (Figure 4), were removed. How well participants adapted affected their pre/post target-pointing. There was a significant correlation, r (49)= .43, p= .001, between the number of errors performed during the late adaptation trials and the pre-post shift so that those who performed fewer errors at the end of adaptation experienced a greater leftward shift in their target-pointing performance. Thus, those participants who better-adapted while wearing the right prisms, actually did show the expected negative aftereffects, which were not observed in the group as a whole

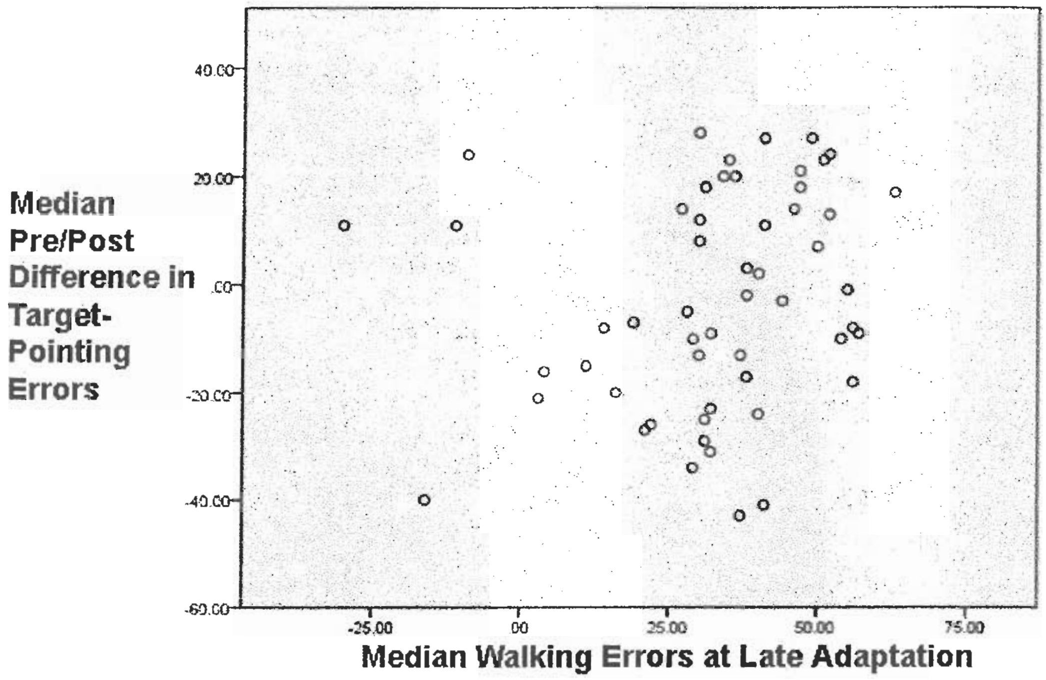


Figure 4. Relation between late adaptation trials and magnitude of target-pointing errors from pretest to post-test for participants who adapted to right goggles.

There was also a significant correlation for those participants who adapted to left goggles, r (50) = .32, p= .011. As is evident in Figure 5, those participants who made fewer errors at the end of the adaptation trials had a more rightward pre-post shift, indicating a negative aftereffect.

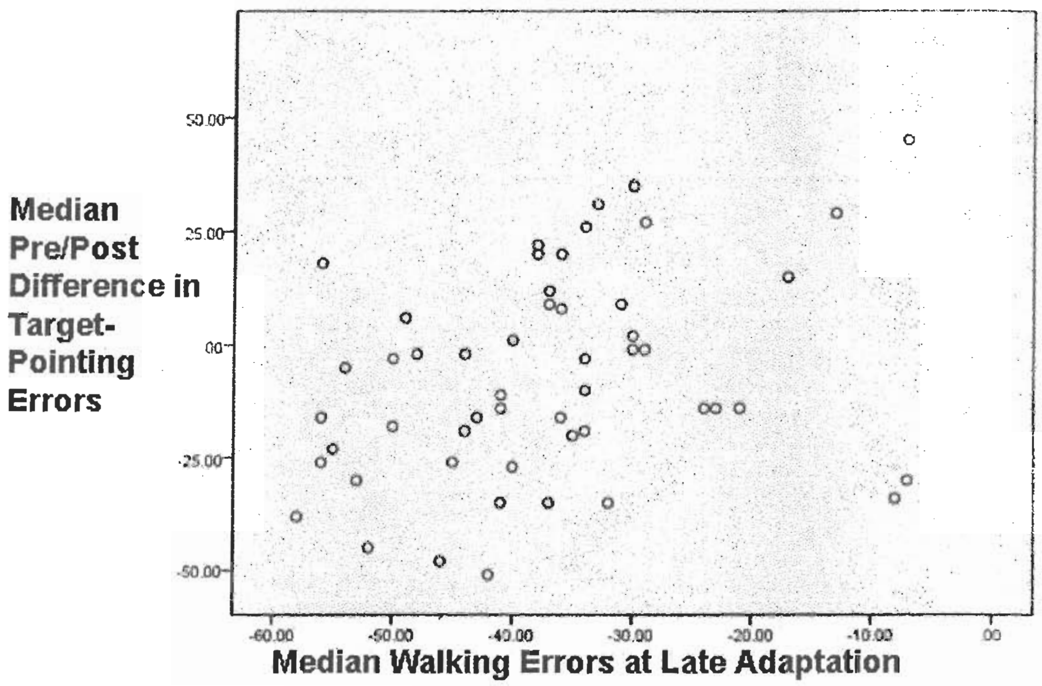


Figure 5. Relation between late adaptation trials and magnitude of target-pointing errors from pretest to post-test for participants who adapted to left goggles.

Walking. The difference score for walking trials was also assessed in order to determine if a correlation existed between the difference in pre/post-test errors and the errors in the late adaptation trials. The correlation was not significant for the right or left goggles, $rs < .16$, $ps > .304$. This indicates that magnitude of errors at the end of the adaptation trials was not correlated with the difference in errors from the pre- to post-test of walking.

Discussion

The goal of this study was to examine the transfer of prism adaptation from a walking task to a target-pointing task. One group was instructed to have error-free performance during the prism exposure adaptation task while another group was permitted to walk naturally, allowing for error. Participants were wearing either left or rightward deviating prisms. It was predicted that the group that was permitted to perform with errors would adapt more and therefore show higher levels of generalization to a target-pointing task, due to their ability to realign. I did not, however, find an effect of instruction condition. The instruction manipulation did not have an effect during adaptation, as those in the error-free condition did not perform significantly fewer errors than those in the natural condition. Consistent with the finding that the instruction manipulation did not produce the expected behavior during adaptation, I also did not find an effect of instruction on the amount of pre to post change in any of the tasks.

I did, however, observe generalization in post-test, as is evident in the differences between baseline and post-test tasks. This indicates that the prisms did have an effect on the participants. Both right and left goggles produced aftereffects. On average, all participants, regardless of the goggles they had adapted with, performed more errors on the post-tests. When examining the goggles separately, only those participants who adapted with left prisms, had performances that were significantly different from baseline to post-test.

Previous studies have indicated that participants show symmetrical aftereffects for left and right prisms when tested on sensorimotor tasks, but asymmetrical generalization to other tasks (Colent et al., 2000, Girardi et al., 2004, Michel et al., 2006). Here, asymmetrical production on the sensorimotor aftereffects was found, with only the left prisms producing a negative aftereffect – i.e., a rightward shift in performance on the visual and proprioceptive shift tasks. Participants who had adapted to left prisms erred more towards the right in the post-tests compared to the pretests, but those adapting to right prisms did not err more leftward in the post-test

The participants in the current study who adapted to left prisms also showed significant effects of the prism adaptation on the target-pointing and walking tasks, while those who adapted to right prisms did not. This latter effect is consistent with the previous findings of asymmetrical effects of left and right prisms on tasks other than visual and proprioceptive shift (Colent et al., 2000, Girardi et al., 2004, Michel et al., 2006). However, the effects of the left prism on target-pointing and walking were not in the expected direction. For both tasks, at the group level, the left prism shifted a right-biased baseline performance more leftward after adaptation. While the current experiment had intended to replicate the findings of Morton and Bastian (2004) who found that right shifting prism adaptation transferred to a pointing task, in addition to showing the production of generalization for left prisms after a walking adaptation, this was not the case. Generalization did occur, though it was not in the direction that was anticipated.

When assessing the results of the individual differences analysis, it is possible to better understand what occurred with the generalization from walking to target-pointing. This analysis revealed that, for the target-pointing post-test, those participants who successfully adapted to the prisms (i.e. showed fewer errors at late than early adaptation), experienced transfer in the expected direction. Participants who successfully adapted to left goggles had more errors that were rightward in the target-pointing post-test. Participants who successfully adapted to right goggles performed with errors that were more leftward in the target-pointing post-test. This indicates a negative aftereffect, which is a measure of learning. These findings reveal that, for those subjects who successfully adapt, transfer to the target-pointing task in the expected direction is possible.

Why More Leftward Shift After Adapting to Left Prisms?

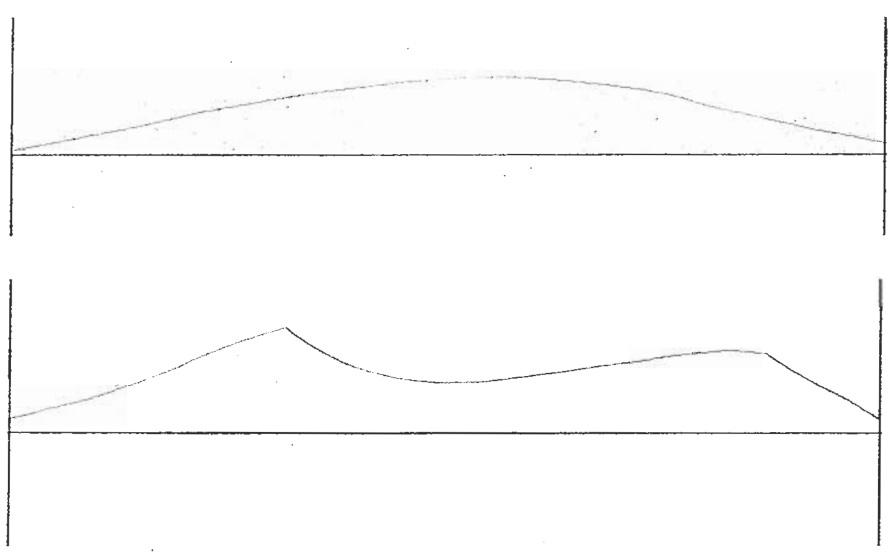
On both the walking and target-pointing tasks, participants performed fewer errors on the post-test than baseline trials. This could be due to practice effects. Another explanation is that a person's system becomes aware of discrepancies by wearing the goggles. This could lead to improved performance once the prisms have been removed. When a baseline performance is already biased, as in our study where all participants were right-biased at baseline, prism adaptation can disturb cognitive functions. In a 2010 study by Bultitude and Woods, participants were asked to identify the global or local forms of hierarchical figures before and after prism adaptation. Participants wore either left or right prisms. Before adaptation, all participants had greater difficulty ignoring irrelevant global information when identifying the local level. Participants who adapted to the left prisms showed reduced global interference, while participants who adapted to right prisms did not show any changes. Our current study is consistent with the results just described, as the participants in the current study made errors in the opposite direction as their baseline performance at post-test. By becoming aware that the prisms have shifted their vision, participants can make attempts, either consciously or subconsciously, to reduce errors on the various tasks they are presented with.

The aftereffects that were found in the current study were in the opposite direction of what was expected: on the target-pointing post-test, participants wearing left prism goggles erred more towards the left. Previous studies have shown that normal young subjects have an a priori leftwards bias when working in peripersonal action space (Jewell and McCourt, 2000). This bias is particularly evident on visuospatial tasks. When young adults are tested on the line bisection tasks, they show negative aftereffects for left but not right prisms (Goedert, LeBlanc, Tsai, & Barrett, 2010). This is likely due to their a priori bias, which creates a ceiling effect in which those trained on right prisms do not show left aftereffects because they are already left biased. Those participants who are right-biased at baseline show reduced aftereffects when training with left prisms, indicating that the failure to generalize has more to do with the participant's a priori bias than the prism.

In the current study, it was found that all of the participants had an a priori rightward bias on all tasks, and their post-adaptation performance moved leftward, consistent with the Goedert et al. (2010) claim that performance can only be pushed in the direction opposite the baseline bias. There is, however, evidence that normal healthy participants have a rightwards bias in extrapersonal space. In the 2001 study by Berberovic and Mattingley, participants were asked to judge the center of a line in either peripersonal or extrapersonal space after adapting to left or right prisms. As expected, participants showed left aftereffects after adapting to right goggles and right aftereffects after adapting to left goggles in the peripersonal task. In the extrapersonal task, all participants showed a rightwards bias after adaptation regardless of prism shift. The findings in the current study can provide further support for this rightwards bias in extrapersonal space, since the target the participants were asked to focus on was over twelve feet away. All participants in our study showed a rightward bias at post-test, similar to the Berberovic and Mattingley findings (2001).

Why Failure of Error-Free/Natural Walking Instructions?

There were no significant differences between the different adaptation conditions. One reason why this may have occurred during walking was the method used to prevent errors in the error-free group. The paradigm we created may have actually caused the error-free condition to have a longer walking path than the natural condition, as they tended to sharply stop and make their way back towards the center when an error was made known. Figure 6 shows an example of a participant in the natural condition and one in the error-free condition. The one in the natural condition made a smooth movement out of the path and back towards the target at the end. Since the error-free participant was made aware of the errors, the participant sharply re-entered the path but then left it again, which resulted in another sharp movement back onto the walkway.



a.

b.

Figure 6. Examples of participants' walking paths in the natural (a) and error-free (b) conditions.

A different method of preventing participants from making errors could be used in the future to keep participants within a walkway without providing an auditory stimulus that causes them to sharply change paths. In the Michel et al. study (2008), participants were instructed to walk within the border of a rectangle. It appears as though the verbal instructions to walk in the rectangle were the only means of keeping them in it; it could have induced error-free walking without informing them every time they left the boundaries. Since Michel et al. did not specifically indicate that this was a means of preventing error, a paradigm was created for the current study that involved telling the participants of their errors in order to urge them back into the walkway. It is possible that by telling them in the beginning to do their best to remain within the path that they would have attempted to do so, thereby creating a walking path that more closely resembles an error-free one.

These findings work towards replicating the study by Michel et al. (2008) on which the experimental paradigm was partially based. They did not find a generalization from walking to pointing using leftward-deviating prisms. Unlike Morton & Bastian (2004), a generalization with the rightward-deviating prisms was not found. In trying to combine the walking adaptation tasks that each of these experiments used, it is possible that the paradigm created was not effective. Instead of informing participants of their errors, Morton & Bastian requested that they walk within boundary lines, while Michel et al. did not attempt to stop the production of errors.

Possible Additional Limitations

One reason that aftereffects on the walking post-tests for the right prisms were not seen could have been due to the time; normal participants tend to de-adapt very quickly once the prisms have been removed (Fernández -Ruiz, et al., 2000). Normal participants can de-adapt within minutes, making it crucial to move them from the adaptation trials to the next task as quickly as possible so that it would be more likely to see the effects of the adaptation. Our participants in the right prism condition may have de-adapted by the time they reached the walking post-test.

It is also possible that participants used strategies to correct their errors. The process of recalibration may have played a role in the lack of expected generalization. Since normal participants are more likely to use strategy than those with spatial neglect (Colent et al., 2000), the participants in this study could have employed strategic methods in order to correct errors. Recalibration, the error reduction that occurs via strategic perceptual motor control processes (Redding and Wallace, 1996), can be used during prism adaptation by participants in order to reduce their movement error through explicit, strategic processes or through more implicit properties. If a participant strategically corrected errors, it would affect the adaptation process and the subsequent lack of generalization in the expected direction to the target-pointing task. Once recalibration occurs, there is no misalignment, which would make realignment unlikely and therefore lead to a lack of learning. This lack of learning could potentially explain the unexpected results seen in the current study at post-test. However, the participants, on average were still making errors at the end of the 25 walking trials during adaptation. So, everyone was not strategically using a recalibration process.

Future research could aim to focus on the mechanisms that underlie the process of generalization. Since few paradigms have been used that have shown that generalization from one task to another is possible, it would be important to attempt to replicate these experiments in an attempt to understand how this happens. Some have suggested that is it a process of visuomotor remapping (Morton and Bastian, 2004), but since the results have been so variable, future research could aim to find the definitive mechanisms involved. A proper paradigm for creating error-free performance could also be useful in discovering the processes of visuomotor learning involved in adaptation tasks.

Conclusions

In summary, our overall findings indicate that participants are more likely to adapt to left than right prisms. This was indicated by the negative aftereffects seen on the proprioceptive and visual shift post-tests in participants who adapted to left prisms and the transfer of walking adaptation to the dot-pointing and walking tasks for the left prisms. Although the current study was unable to determine the effects of error-free versus error-production during adaptation, these results are consistent with an emerging literature on prism adaptation suggesting that it shifts people away from their biased baseline performance on a task rather than just shifting task performance in the direction opposite of the prism shift (Bultitude & Woods, 2010; Goedert et al., 2010).

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Footnotes

[1] For statistical tests that were borderline significant, post hoc power analyses were run in order to determine whether failures to find effects were due to Type II errors. The effect of condition on baseline proprioceptive shift performance approached significance ($p = .080$). The post hoc power analysis of the baseline proprioceptive shift test yielded a power of .96, which suggests this non-significant effect was not due to a Type II error.

[2] For the baseline visual shift test, the goggle by condition interaction approached, but did not reach significant. Post hoc power analyses revealed a power of.42, indicating that this effect may have reached significance were there more participants in the study.

Appendix A

Vertigo Symptom Scale- Short Form

For each of the following, think about the past month, and indicate how often you have felt each of the following in the past month.

1. A feeling that either you, or things around you, are spinning or moving, lasting less than 20 minutes

0	1	2	3	4
Never (most days)	A few times	Several times	Quite often (every week)	Very often

2. Hot or cold spells

0	1	2	3	4
Never (most days)	A few times	Several times	Quite often (every week)	Very often

3. Nausea (feeling sick), vomiting

0	1	2	3	4
Never (most days)	A few times	Several times	Quite often (every week)	Very often

4. A feeling that either you, or things around you, are spinning or moving, lasting more than 20 minutes

0	1	2	3	4
Never (most days)	A few times	Several times	Quite often (every week)	Very often

5. Heart pounding or fluttering

0	1	2	3	4
Never (most days)	A few times	Several times	Quite often (every week)	Very often

6. A feeling of being dizzy, disoriented or "swimmy", lasting all day

0	1	2	3	4
Never	A few times	Several times	Quite often (every week)	Very often

(most days)

7. Headache, or feeling of pressure in the head

0	1	2	3	4
Never	A few times	Several times	Quite often (every week)	Very often
(most days)				

8. Unable to stand or walk properly without support, veering or staggering to one side

0	1	2	3	4
Never	A few times	Several times	Quite often (every week)	Very often
(most days)				

9. Difficulty breathing, been short of breath

0	1	2	3	4
Never	A few times	Several times	Quite often (every week)	Very often
(most days)				

10. Feeling unsteady, about to loose balance, lasting more than 20 minutes

0	1	2	3	4
Never	A few times	Several times	Quite often (every week)	Very often
(most days)				

11. Excessive sweating

0	1	2	3	4
Never	A few times	Several times	Quite often (every week)	Very often
(most days)				

12. Feeling faint, about to black out

0	1	2	3	4
Never	A few times	Several times	Quite often (every week)	Very often
(most days)				

13. Feeling unsteady, about to loose balance, lasting less than 20 minutes

0	1	2	3	4
Never (most days)	A few times	Several times	Quite often (every week)	Very often

14. Pains in the heart or chest region

0	1	2	3	4
Never (most days)	A few times	Several times	Quite often (every week)	Very often

15. A feeling of being dizzy, disoriented or "swimmy", lasting less than 20 minutes

0	1	2	3	4
Never (most days)	A few times	Several times	Quite often (every week)	Very often

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Experimenter Use Only

Subject #: ____________

Total Score: ___________