ARTICLE
Experiencing Visuo-Motor Plasticity by Prism Adaptation in a Classroom Setting

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Neural plasticity is a key topic in the study of behavioral neuroscience, yet it can be a difficult concept to demonstrate in a classroom setting. In this report, we describe an interactive technique that can be used to demonstrate and quantify in a laboratory setting the plasticity of motor coordination to altered visual input, i.e. visuo-motor plasticity. Visual input can be easily altered by horizontally-displacing prism goggles. Open-loop motor coordination immediately after putting on these goggles is inaccurate. However, after performing a number of visuo-motor tasks wearing these goggles, coordination adapts and improves. Immediately after removing the goggles, a robust negative aftereffect resulting from adaptation to the goggles is consistently demonstrated. This negative aftereffect can be used to quantify the amount of adaptation that has taken place. We document how to create the prism goggles, how to quantify accuracy of motor coordination, what kinds of visuo-motor tasks consistently lead to significant adaptation, and the importance of active over passive adaptation conditions.

Key words: neural plasticity, sensory and motor systems, prism adaptation, negative aftereffects.

Sensory and motor systems are central areas of study in any neuroscience curriculum. Didactic lecture courses can provide in depth understanding of the underlying anatomical and neurophysiological substrates of these systems, and how psychophysical and physiological techniques can be used to quantify their function. Understanding how interaction and behavior within our environment hinges on the proper function of these systems can also be clearly demonstrated and experienced by interactive demonstrations in the classroom.

One of the key concepts in the study of sensory and motor systems is neural plasticity, i.e. how experience with the environment can result in neural changes that can often be behaviorally quantified. Many forms of neural plasticity have been demonstrated through alteration of sensory input during critical periods of development. For example, animals that are selectively reared during critical periods in visual environments that only include contours along one orientation develop cortical orientation columns that largely contain neurons specifically responsive to that orientation (Rauschecker and Singer, 1981). Another example is the increase and decrease in volume in somatosensory cortical areas corresponding to body parts that are respectively repetitively trained in or deprived of tactile tasks (Xerri et al., 1996). These forms of neural plasticity would be difficult (and costly) to demonstrate in a classroom setting because they involve animal models and extensive periods of time to demonstrate effects. Reversible forms of neural plasticity that require shorter periods of time to demonstrate, which can be personally experienced by the student, would be better models for teaching this topic in a classroom setting.

One such form of reversible neural plasticity is visuo-motor plasticity. Visuo-motor plasticity involves the coordination between visual input and motor output. If visual input is perceptually altered, motor coordination will be initially inaccurate, but can adapt to the visual alteration after a given adaptation period, subsequently yielding accurate motor actions. One of the classic examples of this kind of plasticity occurs when subjects look through prisms that laterally displace their visual field to the right or left (Held, 1965; Cohen, 1973; Gallahue, 1982). Adaptation to the displaced visual input is best demonstrated if the following constraints are met: 1) the alteration of the visual input must be stable and unchanging over time so that feedback from any initial motor errors is constant, and 2) during the adaptation period, the subject must actively participate in tasks that require some degree of visuo-motor coordination.

It is now largely believed that the cerebellum, a part of the brain that is responsible for the integration of sensory perception and motor control, plays a critical role in visuo-motor plasticity (Gauthier et al., 1979; Weiner et al., 1983; Morton and Bastian, 2004; Tseng et al., 2007). In monkeys, lesions to areas of the cerebellum that receive input from the pontine nuclei of the pons in the brain stem lead to an inability of monkeys to adapt to the visually altered environment (Baizer et al., 1999). Thus it is believed that the proper functioning of these areas of the cerebellum plays a key role in the processing of motor errors when the prisms are first worn, and the subsequent adaptation of motor coordination to reduce these errors.

When introducing visuo-motor plasticity to students, one of the key questions that should be presented at the outset is: Why should organisms have the ability to alter how their visual and motor systems are coordinated in the first place? Over the course of development, our bodies change in size and shape, and thus the ability to alter our motor coordination is imperative for proper interaction with the environment. On a shorter time scale, when a person gets a new prescription for glasses, or wears goggles while scuba diving, the visual input appears initially distorted and may cause motor coordination to be initially inaccurate. However we often quickly adapt to these distortions and learn to make accurate judgments about object locations with respect to our bodies. Visual distortions and motor deficits can result from brain damage or aging, and thus a

system that is plastic enough to accommodate to these changes allows the ability to learn new strategies to accomplish accurate motor actions. It is also important to be able to adjust motor movements to navigate in new environments, for example walking on pavement vs. walking on ice. Lastly, plasticity plays an integral role in ones ability to acquire new motor skills, such as is required in the learning of a new sport or playing a new musical instrument.

This paper describes an inexpensive and engaging technique that enables students to experience visuo-motor plasticity in a small classroom or laboratory setting. We document how to create goggles that contain horizontally-displacing prisms, how to quantify motor coordination, and we describe various visuo-motor tasks that consistently lead to adaptation. All of these can be inexpensively implemented in an experiment that enables students to witness, experience, and quantify adaptation resulting from visuo-motor plasticity.

ADAPTATION TO HORIZONTALLY-DISPLACING PRISMS

How would we interact with the environment if everything was suddenly visually displaced? Imagine, for example, that an object that is physically directly in front of you suddenly appears (incorrectly) shifted to the right. If you were asked to reach out and grab this object, you would initially reach to where the object appears to be, i.e. to the right of where the object really is. Various forms of feedback can provide cues that your hand is not contacting the object: For example, visual feedback may indicate that you are in fact not contacting the object (but perhaps contacting some other object to the right of the desired object). This may cause you to correct your reach, shifting your reach to the left, so that you correctly contact the object. Once your hand contacts the object, visual and proprioceptive cues may conflict because your hand appears visually displaced, but it feels like it is reaching straight ahead (Hay et al., 1965; Botvinick, 2004). In the end, your visual and motor systems will adapt to the fact that in order for you to come in contact with targeted objects, you must reach to the left of where the object appears to be. This adaptation of your visuo-motor coordination (presumably occurring via neural signals from the cerebral cortex to the cerebellum) will occur only if the visual displacement is stable and unchanging over time, and only if you are in fact allowed to actively reach for or interact with the object (and thus realize your errors in a systematic fashion). If instead, you passively view the horizontally-displaced environment without interacting with it, even if you view other people interacting with objects in this environment, your motor coordination will not adapt to the visual shift, and you will inevitably continue to make motor errors. This tells us that it is not just the visual system adapting to the rightward shifted environment (otherwise passive viewing of the altered environment should lead to the same amount of adaptation), but that the motor system is adapting to this visual shift by accommodating motions to the left of where objects appear to be.

The goals of the experiment described here are: 1) to demonstrate to students that they will initially make motor errors when their visual field is displaced, 2) to demonstrate that after some period of interactive visuo-motor tasks, coordination improves, 3) to demonstrate that adaptation as quantified by improved accuracy leads to temporary inaccuracy immediately after the visual displacement is removed, and how this inaccuracy can be used to quantify adaptation, and 4) to demonstrate how adaptation depends on visual and motor interaction with the environment.

There are three major portions of the experiment: 1) the pre-adaptation period, during which coordination is measured before putting on the goggles, and immediately after putting on the goggles, 2) an adaptation period during which subjects leave the goggles on and either perform a series of tasks requiring visuo-motor coordination (active condition), or alternatively watch others perform the same tasks without interacting with them (passive condition), and 3) a post-adaptation period, during which coordination is measured immediately after the adaptation period with the goggles still on, and then again immediately after the goggles are removed.

It is important to note that it is best not to explain the expected patterns of coordination resulting from adaptation before running this experiment, as students may be inclined to think about what their data should look like while performing the various tasks, thus potentially biasing the data.

CONSTRUCTION OF PRISM GOGGLES

Prism goggles can be easily and inexpensively constructed out of regular safety goggles and horizontally-displacing prism lenses. To minimize extraneous visual distortions, safety goggles that have planar frontal surfaces such as those shown in Figure 1*a*-*b* should be used. It is also optimal to choose safety goggles with adjustable elastic bands for comfort. Flexible, vinyl prism lenses (e.g. 3M Press-On Prisms, also known as Fresnel Prisms) are typically applied to eye-glasses to provide prismatic corrections for strabismic patients. These prism lenses refract (i.e. bend) light such that objects viewed through them appear laterally displaced. For this experiment, two of these prism lenses can be applied to the left and right sides of the inner surface of a pair of safety goggles. The prisms can be cut to fit the particular goggles used, and adhered to the goggles under running water (instructions are included with the lenses). The prisms can be easily repositioned (i.e. they are not permanently adhesive). The prisms must be adhered such that the individual facets run vertically parallel on both left and right sides of the goggles (Figure 1*c*), making sure that the prism facets point in the same direction on both sides (Figure 1*d*). When positioned as in Figure 1*d*, the visual field viewed through the goggles will be shifted to the right (Figure 2). Leftward shifts of the visual field can be induced by positioning the lenses such that the facets point in the opposite direction.

We have used 30 diopter prisms to shift the visual field to the right for this experiment, although different strengths can also be used (and manipulated) as instructors see fit. The number of diopters reflects the amount of displacing shift – the higher the diopters, the greater the shift. Thirty diopters specifically shift ones visual field by 16.7 degrees of visual angle. Thus, when looking at an object that is directly in front of you while wearing 30 diopter prisms,

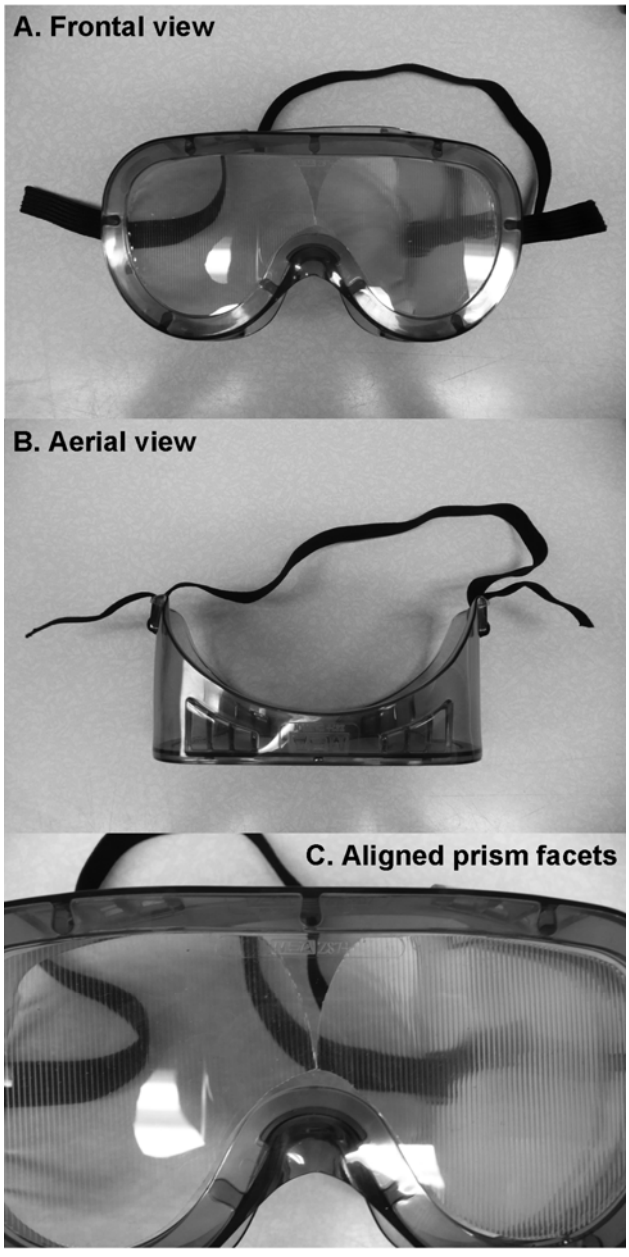

Figure 1. Prism goggles can be constructed from flexible, vinyl prisms applied to the inner surface of flat-frontal-surface safety goggles (*A*-*B*). The prism facets must be vertically parallel (*C*), and aligned such that they consistently shift the visual field in the same direction on both left and right sides of the goggles (*D*).

the distance with which the object appears horizontally shifted (S) will depend on the distance between the you and the object (D, in the same units as S) according to the following equation:

$$S = D * \tan(16.7)$$

For example, an object that is positioned 200 cm in front of you will appear shifted to the right by 60 cm. Note that for prisms of other strengths, the displacement angle in the above equation will be different. The general equation relating the diopters of the prisms to the displacement angle (θ) is:

$$\theta = \text{atan}(\text{Diopters} / 100)$$

Figure 2. View through prism goggles that shift the visual field to the right.

QUANTIFYING MOTOR COORDINATION: OPEN-LOOP POINTING

In order to quantify motor coordination, we use an open-loop pointing task. Subjects should be seated at a desk or table on which is taped a piece of graph paper. For the reasons described above, the distance between the subject's eye and the graph paper on the table should be measured at a fixed distance (e.g. we use a 57 cm piece of string), and maintained for the entire pointing task. The graph paper should have a thick, bold vertical mid-line (the target) marked straight down the middle, as shown in Figure 3. Major distance markers (e.g. inches) on either side of the target should also be marked off across the paper. After being seated at the desk, subjects will be asked to close their eyes, open their eyes for a few seconds, then close their eyes again, and reach out and place a finger on the paper marking where the central target line was perceived to be. With the subject's finger on the paper, other students can then quickly record the

displacement from the target using the marked distances on the paper. Positive numbers should reflect distances to the right of the target, and negative distances to the left. It is important to stress that subjects not view their hands when they perform this task (they should never see their hand in motion) otherwise visual feedback would immediately help them perform the task correctly, obviating the need for an adaptation session. The open-loop nature of this task insures that subjects are coordinating their movements to a previously viewed target without visual feedback. (It is important to emphasize to students that during the pointing task, there should be no feedback for the subject, e.g. snickering, despite how surprising their errors may be.)

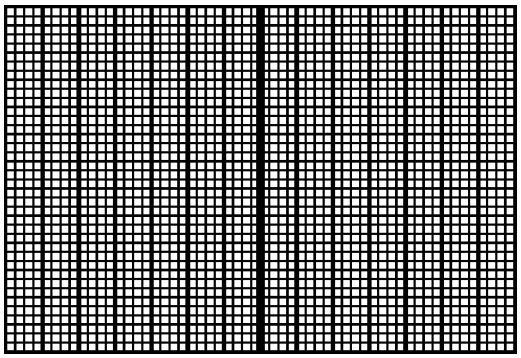

Figure 3. Example of graph paper with central target and indicated major distance markers to facilitate measurement of pointing accuracy.

The pointing task can be used to quantify coordination at four different points in the experiment: 1) before the goggles are put on (to measure baseline open-loop coordination), 2) immediately after the goggles are put on (to determine the initial displacing effect of the prisms on coordination), 3) immediately after adaptation with the goggles still on (to determine if coordination changes after adaptation), and 4) immediately after the goggles are removed (to further quantify the amount of adaptation that has taken place). For reliability, it is a good idea to have subjects point to the target a number of times in each of the four conditions.

ADAPTATION TASKS

Between the pre- and post-adaptation testing periods should be a period of adaptation. We consistently obtain robust adaptation using a 20-minute adaptation period, during which subjects perform four different tasks for 5 minutes each. Instructors can also choose to vary the number of times adaptation tasks are performed, rather than the duration. It is important that these tasks require a substantial amount of hand-eye coordination so that subjects realize and try to correct their errors. It is thus important to indicate to students that they should try their best to perform the tasks accurately. It is crucial that other students guide the subject from station to station throughout this experiment, as the subjects will have difficulty navigating accurately without assistance.

Examples of tasks that we have used that lead to successful adaptation include the following (each of these is repeated for 5 minutes, timed by other students): 1) Have subjects stand 5-6 feet away from a partner (locations can be marked on the floor with tape) and have them toss a beanbag (something soft!) back and forth. If the subject misses the bean-bag, other students should retrieve it for them (subjects should stay standing in place). 2) Tape a container (such as a plastic Chinese food container) onto the floor, situate the subject 5-6 feet away (again the location can be marked with tape), and ask them to toss bean-bags into the container. Once all the bean-bags are tossed, another student should retrieve them for the subject (again, the subject should stay standing in one spot). 3) Gather some coffee or other dried beans. The subject should be seated at a table in front of an empty egg-crate. A second student should hand the subject beans, one at a time, and the subject should place each bean in a compartment of the egg-crate, until all compartments are filled. The subject should then remove the beans one by one, and pass them back to the second student. 4) Use pieces of tape to mark off 20 randomly placed locations on a table top. The subject should be seated in front of this table, handed a deck of cards, and asked to place the cards over the tape marks one at a time, in random order. After all marks are covered, the subject should remove the cards one by one until they are all uncovered.

IMPORTANCE OF ACTIVE VS. PASSIVE ADAPTATION CONDITIONS

As previously indicated, active interaction with the environment during the adaptation period is necessary for seeing any improvement in motor coordination. Thus, it is useful to compare this active condition to a passive condition in which subjects simply watch other students perform the same adaptation tasks. The two conditions can be run on the same subjects in a within-subjects design (optimally on different days) so that subjects experience both active and passive conditions, and witness the differences in their coordination.

QUANTIFYING ADAPTATION: NEGATIVE AFTEREFFECT

After putting on the prism goggles, subjects should consistently show errors in the pointing task in the direction of the horizontal shift. After the adaptation period, however, errors in the pointing task should reduce. One way to quantify the amount of adaptation that takes place is to compare the horizontal displacement in the pointing task immediately after the adaptation period while the goggles are still on (at which point errors should be reduced and subjects should point close to the target) to the horizontal displacement in the pointing task after initially putting on the goggles (which quantifies the initial effect of the goggles, in our example, a rightward shift from the target). A second, more common way to quantify the amount of adaptation is to compare the pointing errors made after the goggles are removed (D_{OFF}, usually in the

direction opposite to that of the shift caused by the goggles) to the errors made after the goggles are initially put on (D_{ON}). The amount of adaptation can be quantified by considering the ratio of D_{OFF} to D_{ON} and expressing it as a percentage:

$$\text{Negative aftereffect} = \frac{D_{OFF}}{D_{ON}} x100$$

This value provides a percentage of adaptation that has occurred: if a subject adapts fully (100%), the initial displacement after putting on the goggles should be fully compensated such that upon removing the goggles after adaptation, the pointing displacement is equal and opposite in direction, thus $|D_{OFF}|=D_{ON}$. If the subject has less than fully adapted, this value will be less than 100%. For the active adaptation condition, we consistently obtain negative aftereffect values in the range of 30-50% using all the parameters described above. This is comparable to what has been reported in other prism adaptation experiments using 30 diopter prisms (Fernandez-Ruiz and Diaz, 1999). In the passive adaptation condition, when subjects watch but do not interact with other students performing the same adaptation tasks for the same duration of time, we obtain values in the range of 10-20%. In our passive adaptation condition, although subjects did not perform the interactive tasks, they were allowed to walk (with guidance) from station to station. The negative aftereffect values could be further reduced if during the adaptation period, subjects were also passively transported (e.g. being pushed around in a chair with wheels) from station to station.

MAKING SENSE OF THE DATA

To quantify how coordination changes over the course of this experiment, students could be instructed to make a bar graph in which the horizontal displacement (away from the target) is plotted for each of the four pointing conditions (during the pre-adaptation phase: before putting on the goggles, and immediately after putting on the goggles, and during the post-adaptation phase: immediately after adaptation with the goggles still on, and immediately after the goggles are removed). Displacements to the right of the target can be plotted as positive numbers, and displacements to the left as negative. Separate graphs can be made for active adaptation conditions (Figure 4*a*) and passive adaptation conditions (Figure 4*b*). Error bars representing standard deviations, standard errors of the mean, or confidence intervals can be plotted to quantify variability and/or significance.

All displacements that differ from zero represent pointing errors. Students can see immediately from these graphs, the conditions under which errors are made, and in which direction. For both active and passive conditions, initial coordination before putting on the goggles should be consistently accurate (displacements close to zero). After donning the goggles, displacements should increase to one side (in our example, to the right). In the active condition, pointing should become more accurate after the adaptation period, much more so than in the passive condition (compare third bar in Figures 4*a* and *b*).

Finally, in the active condition, removal of the goggles should result in displacements in the direction opposite that of the initial horizontal shift (in our example, to the left), whereas in the passive condition, since little or no adaptation will take place, displacements should be close to accurate. To quantify the difference in the amount of

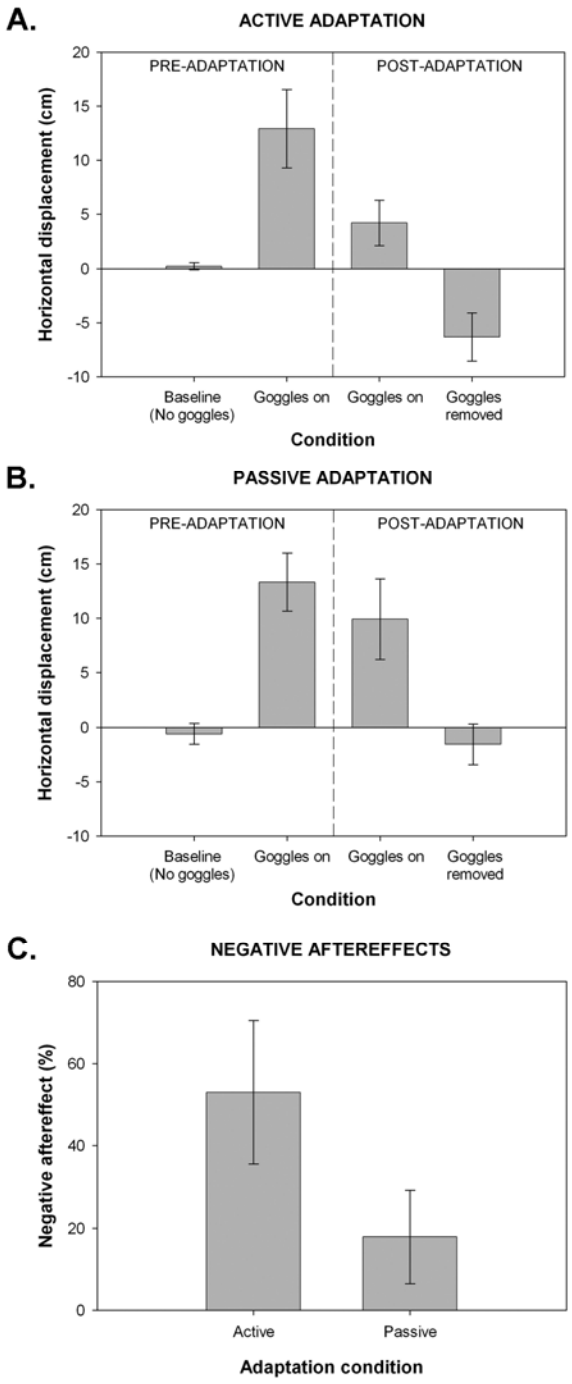

Figure 4. Example data for active (*A*) and passive (*B*) adaptation conditions, and negative aftereffects across both conditions (*C*).

adaptation between the active and passive adaptation conditions, the negative aftereffect (as quantified by the height of the fourth bar divided by the height of the second bar in Figures 4*a* and *b*) could be plotted for each of the adaptation conditions (Figure 4*c*). Negative aftereffects in the active condition should be substantially greater than in the passive condition.

WHAT STUDENTS WILL LEARN

This experiment allows students to experience, personally, yet non-invasively, a form of neural plasticity that occurs over a short period of time. They will experience the immediacy of the consequences of altering ones visual input on motor coordination, and how this coordination can change by interacting with the environment. This experiment is historically not only engaging, but fun for students (even the most coordinated, athletic students will be surprised at how uncoordinated they are at playing catch with these goggles on, additionally students are invariably amused by how frequently they walk or reach for objects inaccurately). The experience of it motivates them to ask questions as the experiment is being run and as the data are analyzed (e.g. Can a person learn to drive with these things on? Who would adapt faster – males or females? Skilled athletes or novices? What would happen if we point with one hand, but adapt with the other? What happens if you wear the goggles upside-down or with one eye closed? Would adapting longer yield greater negative aftereffects?)

While running the experiment, students learn that when subjects put on the goggles, their coordination is, in most cases, completely inaccurate, even though they think they are pointing correctly at the target. This experiment specifically demonstrates one of the basic tenants of any sensory perception course: that ones ability to interact with the environment is strictly dependent on the proper coordination of your sensory and motor systems. Students also learn that adaptation to the prisms results in systematic errors in the opposite direction of the prismatic shift after the prisms are removed, again despite the fact that 1) subjects think they are pointing accurately, and 2) they are no longer wearing the prisms. The difference in negative aftereffects in active vs. passive conditions will teach students that the adaptation does not result from the visual system simply adapting to the shift, but from adaptation of the signals coordinating the visual and motor systems. By testing multiple subjects and multiple trials per condition, students also witness the variability or consistency of data both within and across subjects. When analyzing the data in class, students are invariably surprised by the magnitude of the errors that are made, and how consistent the errors are across subjects.

In the end, students will learn, at a very reasonable cost, about one of the key concepts of behavioral neuroscience, neural plasticity, and through interaction and experimentation, they will learn how it applies to how they interact with their environments. It is our hope that the documentation of this experiment will lead to manipulations of other interesting variables that will lead to other interesting results, and that these sorts of ideas are incorporated into sensory perception and/or behavioral neuroscience courses.

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