PRISM ADAPTATION:
EFFECTS OF TARGET-TYPE AND PERFORMANCE FEEDBACK

by

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SCHOOL OF HEALTH AND HUMAN PERFORMANCE

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled “PRISM ADAPTATION: EFFECTS OF TARGET-TYPE AND PERFORMANCE FEEDBACK” by Matthew P. Ryan in partial fulfilment of the requirements for the degree of Master of Science.

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Signature of Author

Dedications

I would like to dedicate this Thesis to the following:

My parents, Carey and Judy Ryan, for their support throughout this entire process, and convincing me (despite my own uncertainties) that I had the ability to successfully complete this degree. I could not have survived this journey without you.

My supervisor, Dr. Ray Klein, for putting up with my ‘pathological’ fear of failure, for always taking time out of his busy schedule to address my concerns and read my (often lengthy) writing, and for pushing my beyond what I thought I was capable of.

My committee members Dr. Gail Eskes and Dr. Larry Holt for their insight, inspiration, and intelligence.

To my Nanny and Granddad (Ruth and Leo Peddle)
and Grammy (Margaret Trengove-Jones)

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Abstract

When wearing prism goggles that displace vision laterally, the initial pointing errors are rapidly corrected. When the goggles are removed after a sufficient period of prism adaptation (PA), there is an aftereffect in spatial responding in the opposite direction of the original displacement. In this study 24 participants were tested using a computerized PA procedure to explore the effects of displacement direction (left/right), type of feedback during adaptation (hand/indirect), and type of target (fixed/non-fixed) on pointing error during 180 PA trials and the time-course of the aftereffect when measured in two ways: Subjective Straight Ahead (SSA) pointing (proprioceptive guidance towards perceived straight-ahead) and Visual Open Loop (VOL) pointing (visual and proprioceptive performance when pointing toward a straight-ahead target).

During the initial stage of adaptation, all groups adjusted pointing in the opposite direction of prismatic displacement. Pointing error was similar for left and right goggle groups, but was more accurate and faster to stabilize with hand than indirect feedback. After pointing stabilized, the left-goggle/hand feedback group reached beyond targets (‘over-corrected’ pointing error), while other conditions failed to fully adjust pointing and remained ‘under-corrected’.

In all groups, SSA aftereffects were weak or absent, while VOL aftereffects endured for at least 40-minutes. VOL aftereffects were larger following hand-feedback at all post-PA latencies, and for left-goggle groups at early post-PA latencies. Target-type affected performance during the stabilized-phase of adaptation, but did not influence SSA or VOL aftereffects.

These results suggest that computerized PA had induced changes in vision but not proprioception, and provide novel evidence that the technology induced reliable aftereffects following both hand and indirect feedback PA. The results, when considered together with the study’s strengths and weaknesses, provide insight into how future studies might assess computerized-PA can be used to explore more complex attention and space representation process in healthy-normal and patients suffering from unilateral neglect.

List of Abbreviations Used

CNS	Central Nervous System
PA	Prism Adaptation
SSA	Subjective Straight Ahead
VOL	Visual Open Loop

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Chapter 1 Introduction

Prism adaptation (PA) has been used since the 19th century (e. g. Stratton, 1896) to examine visuomotor reorganization in healthy individuals. In a typical prism adaptation (PA) protocol subjects make upper-limb pointing movements toward targets while wearing goggles that displace the visual field to the right or left. Due to the coordination between the visual and proprioceptive systems, the initial points miss targets in the direction of the visual displacement (e. g. points land to the right when wearing right-shifting goggles). When subjects see the hand miss the target, they adjust subsequent points in the opposite direction until accuracy is achieved ("error correction"). Repeated pointing at the correct location causes unconscious adaption in eye–hand systems (vision and proprioception) as pathways in the central nervous system (CNS) are plastically modified (Hein & Held, 1960; Held & Freedman, 1963; Redding, Rossetti & Wallace, 2005; Redding & Wallace, 2006). Following removal of the goggles the new eye-hand relationship is examined by having subjects perform an open-loop pointing task in which straight-ahead points are made without visual feedback of the limb. If adaptation is successful an "aftereffect" is observed in which, relative to pre-PA performance, points fall in the *opposite* direction of the recent prismatic shift.

In 1998 a study by Rossetti and colleagues reported that, following 2-5 minutes of target-pointing performed with goggles that displaced the visual field to the right, unilateral-neglect patients[1] displayed amelioration in right-biased midline perception

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[1] Unilateral Neglect is a condition that occurs in 40-81 % of right hemisphere stroke patients. It is characterized by right biases and left deficits in physical and attention movements, with patients often failing to respond or explore stimuli in the left hemispace (Stone et al., 1993). 'Neglect' leads to difficulties in object location, personal care, eating, dressing and mobility, poor response to therapy, extended hospital stays, and attenuated long term recovery (less than 50 % of neglect patients return to independent living (Stone et al., 1993). Despite extensive investigation, the underlying mechanisms of neglect are unknown, and a standardized method of treatment does not yet exist (Serino et al, 2007).

(blindfolded, straight ahead pointing) and clinical eye-hand tasks (line bisection, line cancellation, figure copying, free drawing). Since these findings, numerous studies have reported improvements in multi-modal attention and space representation, closely related processes, and activities of daily living (Ryan, 2010). However, when the literature is viewed as a whole, improvements are inconsistent, and the mechanisms underlying PA effects are poorly understood.

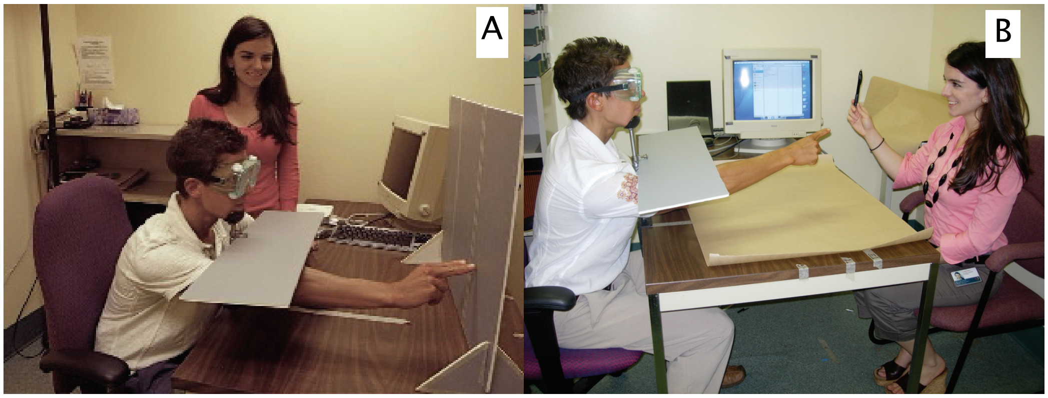

Figure 1.1. Two versions of prism adaptation that investigations have used interchangeably in attempts to ameliorate unilateral neglect, but that differ in characteristics of the targets used during the eye-hand pointing task. In Fixed-target protocols (A), points are directed toward omnipresent left, center or right targets and under directional commands of an experimenter. In Non-fixed target protocols (B) points are directed at left, center or right targets that are presented individually by an experimenter and without verbal commands.

There are several possible reasons for these inconsistencies. First, patient factors such as lesion location (Serino, Angeli, Frassinetti, & Ladavas, 2006; Serino, Bonifazi, Pierfederici, & Ladavas, 2007), time since stroke, and the severity of individuals' unique impairments (Ryan, 2010) may cause PA response to vary. Furthermore, and of particular interest to the current investigation, studies have interchangeably used two distinct target types to adapt patients (Figure 1.1).

Previous research in healthy subjects (Redding and Wallace, 1985, see also Redding and Wallace, 2006 and Redding et al., 2005) suggests that increasing the cognitive demand (e. g. performing mental arithmetic) during adaptation interferes with the process of adaptation (during PA) and the strength/durability of aftereffects within the visual and proprioceptive systems (post-PA). Given that the eye-hand system may share connections with attention and space representation networks, if attentional and cognitive demands differ between the two protocols, the amount of PA-induced modification in vision, proprioception, and spatial perception, representation, and attention may also vary.

Specifics about the two targets will now be described. Twenty-three studies used “fixed” targets (Figure 1.1 A) in which points were directed at omnipresent targets located at patients’ left, right, and center. In the fixed-target protocol, trials were verbally defined by an experimenter who called out a random series of “left”, “right”, or “center” commands. The protocol may place greater demands on limited-capacity cognitive resources to interpret directional commands, use the endogenous [2] attention system to voluntarily orient to the correct target, and resolve conflict between the three aiming responses afforded by the display (a process that may be especially difficult for neglect patients during “center” and “left” pointing trials because of their rightward attentional and movement biases). Meanwhile, seven other investigations used “non-fixed” targets in which subjects generated points toward individually-presented left, right, or center targets, and that were not accompanied by verbal instructions. The sudden-onset nature of

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[2] Endogenous attention refers to voluntary/automatic orienting to a location in space. In contrast, exogenous attention refers to reflexive movement of attention.to the sudden appearance of an external object or event. The neural mechanisms underlying endogenous and exogenous attention are largely independent (Gazzaniga, Ivry, & Mangun, 2002). A meta-analytic review by Losier and Klein (2001) suggested that unilateral neglect is characterized by deficits in exogenous but not endogenous orienting; which is why characteristic differences between fixed and non-fixed targets targets (fixed target and endogenous attention vs. non-fixed targets and exogenous attention) may be important to investigate given PA’s use with unilateral neglect patients.

the targets likely oriented subjects' attention reflexively by way of the exogenous system, there was no processing/interpretation of verbal commands, and inter-target competition for attention and conflict resolution is reduced/eliminated.

From the descriptions above, it appears that PA with fixed targets may require more cognitive resources than PA with non-fixed targets. Therefore, if suggestions made by Redding and Wallace (1985, 2006) and Redding et al. (2005) are applied, interference may be greater during the fixed-target protocol and result in a slowed rate of error correction, reduced strength (magnitude and duration) of the aftereffect. In theory, the minimized cognitive demand with non-fixed targets may result in a faster rate of error correction and strengthened aftereffects. This hypothesized differences between target-type may have important implications for amelioration of neglect-symptoms in patients. If increased in cognitive load (e. g. fixed-targets) interferes with the process of adaptation, and the successful adaptation is associated with amelioration of neglect symptoms (Serino et al., 2006 and 2007), then studies using fixed-targets may have inadvertently made it more difficult for patients to display beneficial effects from PA.

Methodological differences can also be found in the indices used to measure pointing performance during PA and changes in the CNS that follow the exercise. The most commonly observed PA measure is the aftereffect, which represents PA-induced changes in the CNS. It is calculated from open-loop pointing tasks performed before and after PA, in which subjects point straight ahead without visual feedback of the hand (Figure 1.2). The aftereffect occurs when, relative to pre-PA performance, post-PA open-loop points shift in the opposite direction of the recent visual displacement (e. g. post-PA points shift left after PA with right-shifting goggles). The strength of the aftereffect is indicated by its magnitude and duration in which larger and longer-lasting shifts represent stronger PA effects.

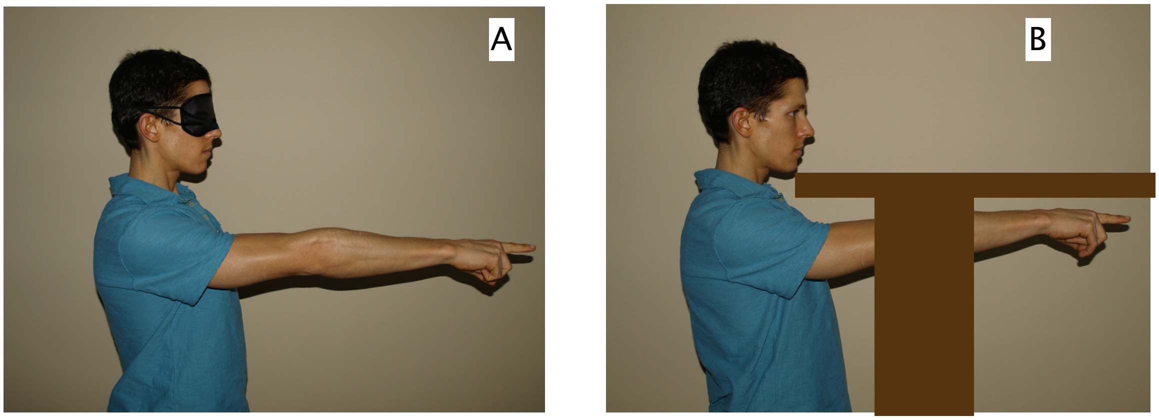

Figure 1.2. Two versions of open-loop pointing that are performed before and after prism adaptation (PA) and that are used to measure changes in the visual and proprioceptive systems (aftereffects). In subjective straight-ahead pointing (A) subjects direct blindfolded points toward their perceived midline, while in visual open-loop pointing (B) points are directed toward a central target with sight of the hand blocked by an occlusion board. An aftereffect occurs when, relative to pre-PA performance, post-PA open-loop points shift in the opposite direction of the visual-displacement (right or left) experienced during prism adaptation. The magnitude and duration of the aftereffect represents the strength of PA effects.

Despite frequent observation of the aftereffect in the PA literature its relationship to neglect amelioration is unclear (Ryan, 2010). Studies have reported that aftereffect magnitude and decay rate fails to predict amelioration (Pisella, Rode, Farne, Boisson, & Rossetti, 2002; Frassinetti, Angeli, Meneghello, Avanzi & Ladavas, 2002; Serino et al. 2006 and 2007). Interpreting the aftereffect’s meaning in neglect-related PA investigations has also been complicated because studies have interchangeably used two, distinct, open-loop tasks. In Subjective straight-ahead (SSA) pointing (Figure 1.2 A), subjects make blindfolded points toward their perceived midline, a task which likely uses the proprioceptive system to guide the hand towards an internal representation of straight ahead (Rossetti, Rode, Pisella, Farne, Li., Boisson & Perenin, 1998). In Visual Open-

Loop (VOL) pointing (Figure 1.2 B), subjects point toward a visible target with the entire limb movement blocked from vision by an occlusion board; a task said to utilize visual *and* proprioceptive systems (Sarri, Greenwood, Kalra, Papp, Husain, , & Driver, 2008; Redding et al., 2005; Redding & Wallace, 2006). A recent meta-analytic and experimental investigation by Sarri et al. (2008) revealed clear performance differences between the indices, and concluded that SSA may be more sensitive for measuring neglect-related phenomena, while VOL is better suited for measuring the relationship between the visual and proprioceptive systems (which is unaffected by neglect).

However, these conclusions may be limited because target type (which may influence the strength of PA effects) was not considered, SSA and VOL aftereffects were based only on initial magnitude and not duration, as they were derived from open-loop tasks performed before and only *immediately* after PA. With regard to the last point, the aftereffect has been shown to exhibit two stages; one that decays in the first-minute post-PA, and another that is durable (>20 min) and shows a slow decay rate (Fernandez-Ruiz, Diaz, Aguilar, & Hall-Haro, 2004). Thus, the single post-PA measurements may not represent the full effect of PA. It is clear that, before definitive conclusions are made about PA effects measured by SSA vs. VOL tasks, their respective durabilities (e. g. multiple post-PA open-loop observations) must be compared following PA with different target-types. Ultimately, experiments must determine whether aftereffects measured by SSA and/or VOL provide useful information for neglect-related investigations.

Pointing error (horizontal distance from visual targets) is used to the measure the learning process that occurs *during* PA (hereafter referred to ‘Adaptation’). Due to yoking between the eye and hand, the goggle-induced visual displacement causes initial pointing trials to miss targets in the direction of the goggle shift. During the initial phase of adaptation, a process known as 'error correction' occurs when subjects use performance feedback and adjust pointing behavior (shifting points opposite the goggle-shift) to overcome the displaced visual field, and make points accurate. For the sake of clarity, because error correction occurs *during* PA, it is a different 'shift' in pointing than the aftereffect (which occurs *after* goggle removal). Following error correction, pointing error typically stabilizes for the remainder of pointing trials.

Whereas Serino et al. (2006 and 2007) did not find a significant relationship between the aftereffect and neglect amelioration, they did find that patients that were able to successfully correct pointing error also displayed the greatest amelioration of neglect symptoms. The latter finding lead them to suggest that error correction is a predictor of patients benefitting from PA. Unfortunately, despite its potential value, difficulties associated with manually measuring pointing error during adaptation have made PA scholars reluctant to collect or report the pointing error during adaptation. This is unfortunate because (on the assumption that there is a relationship between error correction and neglect amelioration) those not observing pointing errors during adaptation may have unintentionally confounded results by including patients who were unable to make error correction and correspondingly failed to benefit from PA.

Furthermore, research has yet to determine if/how the pattern/rate of error correction may be related to post-PA sensory-motor, perceptual and attentional, and if these vary with the target type used during adaptation. Ultimately, if the proposed relationship between error correction and amelioration is true, information obtained about error correction may be useful for determining which target-type optimizes beneficial PA effects.

It is clear that patient and methodological issues have likely contributed to the poor understanding of PA as it relates to neglect. Furthermore, research is required to explore the differences between fixed and non-fixed targets with respect to error correction and both types of aftereffects (SSA and VOL), while overcoming undermining factors posed by patients and manually presented/measured protocols.

Overcoming contamination of results from effects of brain injury can be accomplished with PA investigations carried out with healthy subjects. Specifically, studies that expose healthy-normals to left-displacing prism goggles have been shown useful for gaining an understanding of the mechanisms that underly PA-induced neglect amelioration. Left-goggle PA has been shown to induce transient, neglect-like behavior in multiple modes of spatial perception and attention (e. g. Colent et al., 2000; Berberovic & Mattingley, 2003; Michel, Pisella , Halligan, Luaute, Rode, Boisson, & Rossetti, 2003; Girardi, McIntosh, Michel, Vallar, & Rossetti, 2004; Rossetti, Jacquin-Courtois, Rode, Ota, Michel, & Boisson, 2004), which suggests common brain mechanisms are being modified in healthy normals and patients (for review see Michel, 2006).

The transition of PA to computerized formats may help overcome the manual presentation and measurement issues that characterize PA studies in the current PA literature. In computerized PA subjects direct points at a touch-sensitive computer interface that presents targets and records precise measurements of pointing error (where finger contacts the screen) during adaptation or open-loop tasks. Because stimulus presentation is easily manipulated and measurement of error correction and aftereffects are automated, programs can be designed that allow the literature’s methodological issues (e. g. fixed vs. non-fixed targets and VOL vs. SSA pointing) to be explored with a high-level of experimental control.

Beyond its capacity to resolve current issues in the field of PA, computerized PA affords the opportunity to incorporate new features into the PA protocols test out how they impact the adaptation process and the strength of PA effects. One feature that has undergone preliminary investigation is the provision of indirect accuracy feedback during adaptation (e. g. Clower & Boussaoud, 2000; Wilms & Mala, 2010). In these conditions, points are directed toward targets on the touch screen, but (similar to VOL) the entire movement is blocked from vision. Rather than receiving accuracy feedback directly from vision of the hand/finger when it emerges from under the occluder, feedback is provided "indirectly" in the form of a computerized stimulus (e. g. an ‘x’ or a vertical line) appearing at the location of contact.

When Clower & Boussaoud (2000) and Wilms & Malá (2010) compared the VOL aftereffects following PA with indirect and hand feedback, the aftereffect magnitude was either non-significant or significantly smaller in the indirect-feedback condition. Both studies took this as evidence that subjects were unable to relate the indirect performance feedback directly to the bodily act of pointing and, because this association is necessary for modifications to vision and proprioception (Welch, 1994; Welch & Warren, 1980), aftereffects were absent or small. For this reason it was suggested that indirect-feedback may not be useful in PA aimed at ameliorating unilateral neglect (Wilms & Malá, 2010) .

The findings from Clower & Boussaoud (2000) and Wilms & Malá (2010) are limited for several reasons. First, healthy-subjects were adapted with either left goggles (Clower & Boussaoud, 2000) or right goggles (Wilms &Mala, 2010), but without a between-goggle comparison. Second, the aftereffect magnitude was measured *immediately* following PA, which, if the suggestion by Fernandez-Ruiz et al. (2004) is applied, may represent 'fast-decaying' aftereffects rather than a durable ones that represent the 'true' PA effects. Third, the aftereffect's long-term duration, a key component for interpreting the strength of PA effects, was not considered. Fourth, the aftereffects were based on VOL pointing only, which, if suggestions made by Sarri et al. (2008) are applied may not be as useful for measuring neglect-related phenomena as SSA tasks (which were not performed). A final, salient, weakness of this study is its failure to capitalize on computerized PA's automated collection of pointing performance and make closer inspections of patterns performance during adaptation (e. g. error correction and after pointing stabilized during adaptation), and how these may have carried-over to the aftereffects. This is an unfortunate oversight given that error correction (Serino et al. 2006 and 2007) and performance during the stabilized phase (Redding & Wallace, 2006) have both been implicated as important in PA's amelioration of neglect, yet the relationship between characteristics of adaptation, aftereffects, and modification to neglect's underlying mechanisms remains unknown.

Thus, before definite conclusions can be made about the effectiveness of computerized PA effects (including those about smaller aftereffects from indirect feedback), studies must be carried out that have healthy-normal patients perform PA with left-shift and right-shift goggles, in which the magnitude *and* duration of SSA and VOL aftereffects are assessed, and where characteristics of error correction and the aftereffect are considered with equal importance and examined for possible relationships.

Purpose

The purpose of this study was to address a number of methodological and measurement issues in the neglect-related PA literature, and with the specific intent of fully investigating the unknown effects of PA with different target (fixed vs non-fixed) and feedback (hand vs. indirect feedback) types on characteristics of adaptation *and* aftereffects (with equal emphasis placed on both). To fulfill these objectives, we took advantage of the measurement and stimulus presentation capacities afforded by computerized PA. In addition, in order to avoid possible contamination of results due to brain injury, while maintaining a neglect-related scope, healthy-subjects underwent the various forms of PA with right-shift or left-shift prisms. Finally, to confirm previous findings that VOL *and* SSA aftereffects are differentially sensitive for measuring neglect-related phenomena (e. g. Sarri et al., 2008) both open-loop tasks were assessed.

Specifically, 24 healthy-subjects performed in two adaptation sessions with various combinations of target (fixed vs. non-fixed), goggle (left vs. right), and feedback (hand vs. indirect). Target type was manipulated between sessions, while goggle and feedback type were held constant and varied between groups. Within each session SSA *and* VOL open-loop tasks were performed in one pre-PA block and five post-PA blocks (one block immediately following goggle removal, with others separated by 10-min rest intervals). Of particular interest to the investigation was how target, goggle, and feedback type influenced the rate/pattern of error correction (during PA), and the magnitude and duration of SSA and VOL aftereffects (post-PA).

Adaptation and aftereffects were quantified by the computerized technology, which recorded precise measurements of the horizontal distance horizontal distance (in pixels) between the finger's touch location and the left, center or right target (during PA) or the center of the touch screen (SSA and VOL pointing). Collection of sequential pointing trials during PA allowed the pattern/rate of error correction to be observed and how this differed between the various PA conditions. SSA and VOL aftereffects were calculated separately. The magnitude for each post-PA block was obtained by way of a post-pre difference score (distance from center of touch screen post PA - distance from center of touch screen pre PA). Duration was observed in how the magnitude changed as a function of post-PA block.

The comprehensive nature of the study would hopefully provide preliminary evidence for which target and feedback types are best for facilitating adaption and inducing strongest PA effects; information that may prove useful for planning future (computerized-based) PA studies that will investigate how different types of PA affect complex attention and space representation processes. Ultimately, the findings from this computerized PA study will lay the foundations for gaining a full understanding of the underlying mechanisms of PA, and the types of PA that optimize amelioration of neglect in patients.

General Adaptation Hypotheses

It was anticipated that during adaptation initial pointing trials would show the largest pointing error, but that performance feedback would be used to adjust movements in the opposite direction of the goggle shift until performance was accurate (error correction). Furthermore, this ‘error correction’ would occur within 10-15 trials, and would stay accurate for the remaining trials. These expectations applied to all combinations of goggle and feedback type, based on previous PA studies (e. g. Berverovic & Mattingly, 2003; Clower & Boussaoud, 2000; Redding et al., 2005; Redding & Wallace, 2006). Any differences that emerged between the various PA conditions in terms of the pattern/rate of error correction or pointing when performance had stabilized would indicate which factors may have caused attentional processing and/or cognitive demands to vary and affected adaptation as a result.

Specific Adaptation Hypotheses

Based on previous PA investigations that examined differences in PA with left-shift and right-shift goggles (e. g. Berverovic & Mattingly, 2003) it was expected that both goggle groups would show similar initial pointing error, error correction, and level of accuracy (e. g. horizontal distance from targets) when pointing stabilized. Similar adaptation patterns were also expected for PA with hand-feedback and indirect feedback based on reports from previous computerized PA investigations (Berverovic & Mattingly, 2003; Clower & Boussaoud, 2000; Wilms & Mala, 2010)[3].

On the other hand, given that cognitive load appears to be increased during fixed target-PA, and increases in cognitive load interferes with adaptation (Redding & Wallace, 1985), it was hypothesized that the rate of adaptation would be slower (e. g. more points needed to fully correct initial pointing error and make points accurate) in PA with fixed-

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[3] Although previous computerized PA investigations (Clower & Boussaoud, 2000; Wilms & Mala, 2010) had not carefully considered the importance of adaptation performance, or related to the aftereffect, both did report that subjects had successfully corrected pointing error, and that direct and indirect conditions had not shown significant differences in pointing errors during PA.

targets compared to PA with non-fixed targets.

General Aftereffect Hypotheses

The strength of PA effects on the visual and proprioceptive systems (VOL), and internal representation of space and proprioception (SSA) would be indicated by the magnitude *and* duration of aftereffects. It was expected that, relative to pre-PA performance, SSA and VOL points would shift in the opposite direction of the goggle-type used during PA (right-goggle, left-aftereffect), that the change would be largest immediately following PA, and show decay back to pre-PA levels over the course of 40-minutes.

Specific Aftereffect Hypotheses

Based on findings that PA with left-goggles induces neglect-like symptoms in healthy subjects (e. g. Berberovic & Mattingly, 2003 and Michel, 2006), and that SSA is the more sensitive measure of neglect-related phenomena (e. g. pre-PA right bias and post-PA amelioration in patients) (Sarri et al., 2008) it was expected that the SSA aftereffects following left-goggle PA would be characterized by a large-magnitude, long-lasting SSA aftereffect, especially for target and feedback types that have the largest affect on the underlying mechanisms of neglect. In contrast, given findings that neglect-patients and healthy-normal exhibit similar VOL aftereffects (Sarri et al., 2008), it was expected that, even if left-goggle PA stimulated neglect-like behavior, the strength of the VOL aftereffects would be relatively consistent across right and left goggle groups, and all combinations of target and feedback type.

Given that the hypothesized increase in cognitive demands for PA with fixed targets was expected to interfere with PA-induced modifications to the vision and proprioception during adaptation (Redding & Wallace, 1985), it was hypothesized that SSA and VOL aftereffects would be weaker (e. g. smaller magnitude, faster decay) following PA with fixed-targets compared to non-fixed targets.

Based on two previous computerized PA investigations (Clower & Boussaoud; 2000 and Wilms & Mala, 2010, aftereffects that followed hand-feedback PA were expected to show a larger magnitude *and* longer duration than those following indirect-feedback PA.

Chapter 2 Methods

2.1 Subjects

The subjects were 24 healthy subjects, 8 male (*M*= 25.0 , *SD*=1.60 years) and 16 female (*M*= 23.5, *SD*= 2.5 years), all of whom self-identified as being free of cognitive impairment, and having normal or corrected-to-normal vision and hearing. Twenty-one subjects reported right-hand dominance, with the remaining 3 (all male) identifying as ambidextrous (two reported right-hand preference in all hand-eye tasks except writing, and one reported equal preference for both hands in all hand-eye tasks). A summary of subjects' demographic information can be found in Appendix A.

Table 2.1.
Possible combinations of goggle and feedback type (left) and order of target-type (right) to which subjects could be assigned in a two-session prism adaptation experiment. For each subject, goggle and feedback type was held constant for the two sessions, while target-type was manipulated from Session 1 to Session 2.

		Goggle Type	
		Right	**Left**
Feedback Type	**Hand**	Condition 1 Right + Hand	Condition 2 Left + Hand
	Indirect	Condition 3 Right +Indirect	Condition 4 Left + Indirect

	Session 1	**Session 2**
Target Type	Fixed	Non-Fixed
	Non-Fixed	Fixed

2.2 Apparatus

2.2.1 Prism Goggles

Subjects performed PA pointing tasks wearing the prismatic goggles (safety goggles fitted with Fresnel Prisms) that displaced the visual field 10 deg. to the Left or Right (Figure 2.1).

Figure 2.1. Safety goggles fitted with Fresnel Prisms, and that were used to displace the visual field to the left or right during the prism adaptation pointing task.

2.2.2 Touch Screen

The system used to present targets, record point locations, and provide accuracy feedback was a Smartboard interactive whiteboard (156.5 cm long x 117 cm tall, Figure 2.2 C) connected to a laptop computer (Dell, Latitude E6500, Intel Core Duo CPU P8600 @ 2.40 GHz 2.40 GHz with 2.0 GB of RAM and running Windows Vista Business, SP1). The laptop ran a Python program (Python, Version 2.5.2)[4] that generated targets (PA and Open-Loop) and provided indirect feedback (where applicable) on the Smartboard surface, presented auditory commands and feedback, and collected error correction and straight-ahead pointing data. The Smartboard's collection of pointing errors was enabled by resistive technology. When the finger came into contact with a resistive film on the screen, an analog signal of the point of contact was sent to the laptop and was recorded/ stored in the Python program.

2.2.3 Occlusion Boards

An occlusion board (Figure 2.2 B) fully or partially blocked sight of the hand in open-loop and PA pointing tasks. The occlusion board was positioned between the participant and the touch screen apparatus, and consisted of a horizontal piece of foam

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[4] Written by Joshua Salmon

board (0.5 cm thick) placed between two vertical posts (Figure 2.2 B). The foam board could be raised or lowered to to accommodate different subject heights. The open space between the two vertical posts and beneath the foam board allowed subjects to make unobstructed reach/touch movements toward the Smartboard. Two lengths of occlusion board were used (“short” and “long”), depending on if the pointing task required visual feedback of the hand.

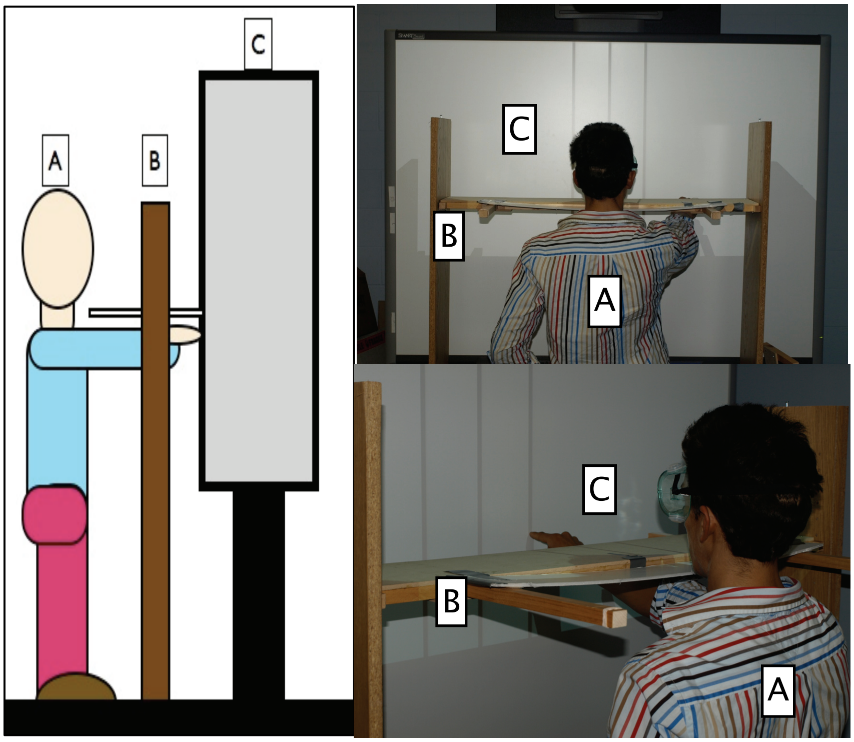

Figure 2.2. Illustration (left) and photographs (right) of the computerized PA set-up. An occlusion board (B) that was positioned between the participant (A) and the touch screen apparatus (C) fully or partially blocked feedback of the hand, while the touch-screen presented targets and recorded precise measurements of pointing error during prism adaptation and open loop pointing tasks.

The short occlusion board extended from below the participant’s chin and half-way to the Smartboard. It blocked the hand’s initial position and first half of a pointing movement, yet allowed for visual feedback of the hand for the second half of the pointing movement and the location where the finger contacted the Smartboard.

Occluding the first portion of the pointing movement in the hand-feedback tasks was necessary to facilitate adaptation to prisms. Based on evidence showing that when the hand is available to vision from the start to finish of the point, subjects use online-feedback (during the movement) to guide the hand to the target and modification to the visual and proprioceptive systems (e. g. “aftereffects) do not occur (Redding & Wallace, 1992 and 2006; Redding et al., 2005).

The long occlusion board spanned the distance from below the patient’s chin to the surface of the Smartboard during indirect-feedback PA conditions and the VOL pointing tasks, both of which required subjects to point towards visual targets on the touch-screen but required sight of the entire movement to be blocked.

2.2.4 Video Goggles

During the ten-minute intervals that separated the post-PA blocks of open-loop pointing subjects donned a pair of video goggles (Zetronix z920HR-VGA, see Figure 2.3) and watched a popular animated sitcom. The purpose behind the video-goggles was to increase the validity of our measurement of the aftereffect’s time-course by preventing interaction between the eye and the hand. This objective was based on evidence that the aftereffect’s rate of decay increases when the eye and hand are allowed to interact (Fernandez-Ruiz & Diaz, 1999).

Figure 2.3. Video Goggles were worn during the 10-minutes separating open-loop pointing blocks. This prevented interaction between the eye and the hand, and slowed the decay of SSA and VOL aftereffects (Fernandez-Ruiz & Diaz, 1999).

2.1 Design

Subjects were randomly assigned to one of the four combinations of goggle and feedback type (Table 2.1). Each participant completed two PA sessions, one with fixed-targets and another with non-fixed targets (order of target-type was counter-balanced within each condition). Assignment to order of fixed and non-fixed target conditions was counter-balanced across subjects in order to prevent effects of the target-order. In addition, goggle-type (e. g. right or left displacement) was not disclosed to the participants so that accuracy feedback (hand or indirect) would be used to correct pointing error rather than prior knowledge of the goggle shift. In total, 5 subjects completed PA with left-goggle/hand-feedback, 6 with left-goggle/indirect-feedback, 6 with right-goggle/hand-feedback conditions, and 7 with right-goggle/indirect feedback (Appendix A)[5] .

2.4 Procedure

2.4.1 Positioning Subjects

Subjects performed PA and Open-loop pointing tasks standing centrally and at an arm's length distance with respect to the Smartboard. In order to ensure subjects returned to this same position during the various stages of the experiment masking-tape markers were placed on the floor in front of the toes, and at the lateral edges of the feet. In addition, the experimenter measured the horizontal distance from the touch screen to the center of the subject's right shoulder. This distance was entered into the target-generating computer program that calculated the left and right target locations (10 deg. to the left and right) based on each subjects' unique distance from the Smartboard.

A single experimental session consisted of a baseline set of pre-PA open-loop points, a ten-minute prism adaptation protocol, and five, post-PA sets of open-loop points. The post-PA sets of open-loop pointing were separated by ten-minute intervals, at which time subjects rested comfortably in a chair and watched an animated sitcom on a pair of video-goggles. The experimental sequence is displayed in Figure 2.4, and descriptions of the components will be provided thereafter.

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[5] The uneven numbers in each experimental condition were a consequence of attrition or abnormal performance. Two subjects within the left-goggle/hand feedback condition and one subject within the left-goggle/indirect feedback condition did not complete both testing sessions. Upon preliminary examination of the data, in was revealed that one subject in the right goggle/hand feedback condition had not corrected pointing error or demonstrated aftereffects in either experimental sessions. Data from these four subjects were omitted from the analyses.

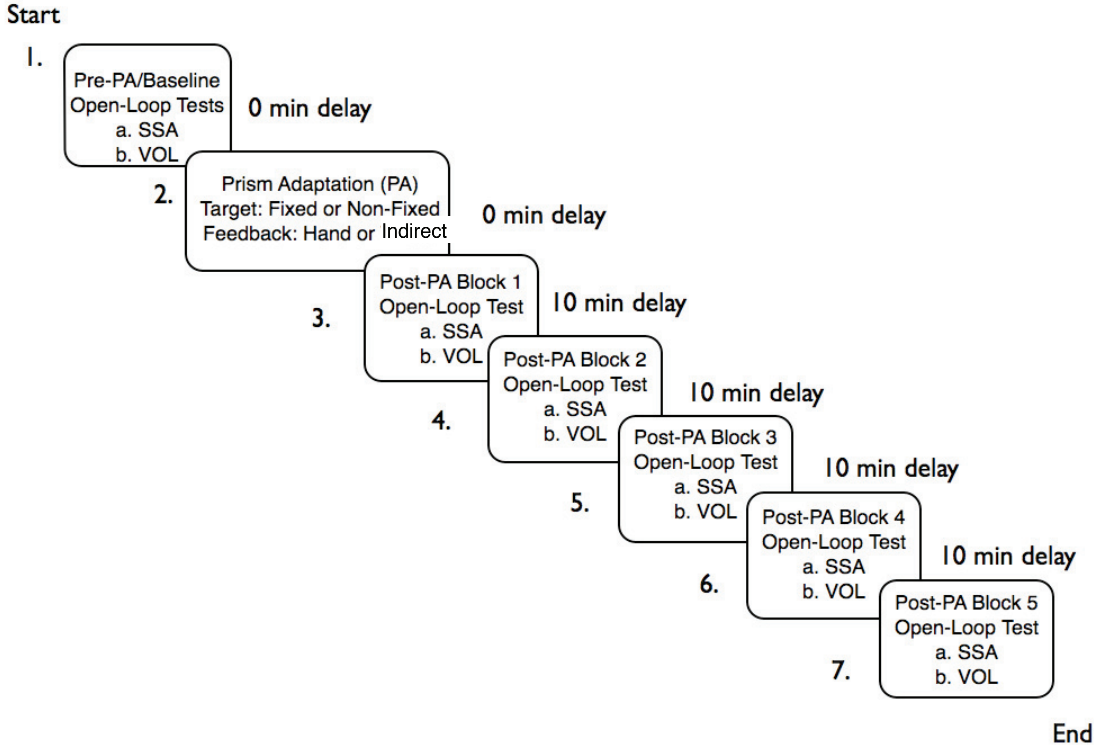

Figure 2.4. Task order of a single experimental session investigating how prism adaptation with different types of goggle, target and feedback effects characteristics of adaptation and aftereffects in healthy subjects.

2.4.2.Open-Loop Pointing

The first task performed was one block of Open-loop points, which consisted of 10 SSA points and 10 VOL points, and separated by a 10-s break (at which time the blindfold used in SSA was removed). This initial block served as the baseline (pre-PA) measure of performance of the visual and proprioceptive systems, and which were expected to undergo a post-PA change. Specifically, this first block of SSA points demonstrated normal performance of the proprioceptive system (guided by an internal representation of straight-ahead), and VOL the visual and proprioceptive systems.

In both Open-Loop tasks subjects placed the right hand on the chest (at the level of the sternum) and upon hearing a computer-generated “go” command reached forward, touched the Smartboard's center with the index finger, and returned the hand to the chest. If the Smartboard registered the point, auditory feedback ('ding') sounded as the subject returned the hand to the chest. The next 'go' command sounded 1.5 s after contact was registered. One reach-touch-return movement constituted a single pointing trial.

In the SSA task, subjects donned a blindfold and made 10 straight-ahead points to the position on the Smartboard they perceived to be in line with the center of their body[6]. Following the SSA points, they remained in the same standing position, removed the blindfold, and commenced the VOL task. In VOL subjects made 10 points toward a single, vertical line located at the center of the Smartboard. In both open-loop tasks the "Long" occlusion board was present, but only blocked sight of the hand in the VOL task (the blindfold fulfilled this purpose in SSA).

In all blocks of open-loop pointing, SSA always preceded VOL in order to prevent subjects from directing SSA points to a remembered-position of the visual target used in VOL task (rather than their own internal representation of straight ahead).

To measure PA-induced changes in the visual and proprioceptive systems the series of 10 SSA and 10 VOL points was repeated in five blocks following PA (Figure 1.2). The first post-PA block was performed immediately after subjects completed the PA protocol and removed the prisms goggles. The remaining four blocks were separated by ten-minute rest intervals, during which time subjects donned video goggles (Figure 2.3) and watched a popular animated sitcom.

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6 Prior to donning the blindfold in the SSA task, subjects were instructed to imagine looking into a mirror and directing points toward the center of their reflection

2.4.3 Prism Adaptation

Immediately following the first block of Open-Loop points, subjects remained standing in front of the touch screen (central and at an arms-length distance), put on their assigned prism goggles, and performed a ten-minute PA protocol. In all protocols 180 right-handed points were made toward targets located at center and 10 deg. to the left and right with respect to their midline (60 pointing trials/direction).

A pointing trial began with the sounding of a computer-generated auditory command (A non-spatial "go" command in non-fixed target conditions, and "left", "right" or "center" directional commands in the fixed-target conditions). In response, subjects initiated a point from the chest, extended the arm, attempted to touch appropriate target (black, vertical lines that spanned from the bottom to the top of the Smartboard screen) with the index finger, and returned the hand to the chest. Prior to starting the protocols, subjects were instructed to pay attention to the index finger's location of contact (provided by hand or indirect feedback) with respect to the intended target, and use it to make subsequent points accurate. If touch location was registered by the Smartboard, an auditory 'ding' sounded. If the touch was not registered (indicated by absence of the auditory 'ding' feedback), the trial was repeated. The next initiation command was delivered 1.5 s later (pending registration of the touch). The timing of the commands and auditory feedback created a pointing cadence of approximately one point every 3 s (time between the hand leaving and returning to the chest). Specifics details about each target/feedback condition will now be described.

In addition to Right vs. Left goggle-type, the main experimental manipulations were target type (fixed vs. non-fixed targets) and feedback type (Hand vs. Indirect Feedback). Details about the latter two conditions are as follows.

Fixed vs. Non-fixed target

In fixed-target conditions center, left and right targets were omnipresent on the Smartboard throughout the PA protocol. A series of “left”, “right” or “center” auditory commands sounded in random order, and subjects responded by attempting to touch the appropriate target with the index finger. In the non-fixed target conditions a series of right, center or left targets appeared one-at-a-time in random order. To control for alerting effects of the directional commands in the fixed-target condition, non-fixed targets were accompanied by computer-generated, non-directional “go” commands. In response to the appearance of a target and auditory cue, subjects extended the arm and attempted to touch the target on the Smartboard. If the touch was recorded the non-fixed targets disappeared 1 s after the auditory ‘ding’ feedback.

Hand vs. Indirect Feedback

In hand-feedback conditions, a short occlusion board was used to prevent sight of the hand’s starting position or first half of the pointing movement, but to allow for sight of the hand/finger in the second half and touch-location. Prior to beginning the protocols, subjects were instructed to observe the location of the index finger with respect to the intended target and use the feedback to make subsequent points accurate. In the indirect feedback conditions a long occlusion board was used to prevent sight of the entire pointing movement. Performance feedback came in the form of a vertical, red line that appeared for 1 s at the location where subjects touched the screen (and was accompanied by the auditory ‘ding’ feedback). Subjects had been instructed to observe the location of the red line with respect to the intended target as they returned the hand to the chest, and use the feedback to make subsequent points accurate [7] . A difference between the non-fixed and fixed-target conditions that used indirect feedback was the disappearance of target *and* feedback lines after 1 s in the non-fixed target condition (targets were omnipresent in the fixed-target condition).

2.5 Methods of Statistical Analysis

Statistical analysis on adaptation and aftereffects were performed using the computing environment R (R Development Core Team, 2005). For adaptation, pointing errors (horizontal distance from the intended targets, relative to the direction of the goggles in pixels) were submitted to a mixed, repeated measures ANOVA with goggle (left vs. right) and feedback (hand vs. indirect) type as between-subjects factors and target-type (fixed vs. non-fixed) and trial(pointing trials 1-180)[8] as within-subjects factors. For the aftereffect, five difference scores (one for each post-PA block) were calculated based on the performance of SSA and VOL pointing tasks (measured as the mean pointing error from the center of the Smartboard, in pixels) performed once pre-PA and five-times post-PA. Difference scores were submitted to another mixed-repeated measures ANOVA with goggle and feedback type as between subjects factors and target-type (fixed vs. non-fixed), block (post-PA block 1-5), and blind (SSA vs. VOL task) as within subjects factors. More detailed description of how the adaptation and aftereffect

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[7] Subjects were told the goal was to get the red line to appear on top of the correct target.

[8] For the adaptation analysis the variable of trial (1-180) was treated as numeric and therefore any main effect of trial represents a linear trend, and the degrees of freedom associated with trial is 1 rather than 179.

data were analyzed are found in results section that follows. Visualizations of significant effects and interactions from the analyses were created in pro Fit 6. 1. 10.

Pointing error data was recorded in pixels that had been calculated using trigonometry (based on the distance participants were from the screen, and which had been based on their measured arm length). However, PA studies typically report error correction and aftereffect measurements using degrees of visual angle. In order to make the current study's results comparable with other literature, it was necessary that degrees of visual angle be included in the visualizations of significant effects of goggle, target, and feedback type on adaptation (pointing errors) and aftereffects (difference scores). Through a series of mathematical and statistical operations, it was determined that there were, on average, 13.8 pixels per visual angle, and that dividing score by the pixel data by this constant (13.8), the statistics, results, and interpretations thereof would not change (only the scale of the pointing error or difference score). Details of the conversion process are located in Appendix B.

Chapter 3 Results

The following sections will start by reporting the results from the analyses on adaptation and open-loop pointing portions of the experiment. Significant effects and interactions will be reported, displayed graphically, and notable patterns described. Following separate consideration of the adaptation and open-loop pointing results, the graphical representations from the two components will be compared directly with the intent of observing possible relationships between them.

3.1 Adaptation

The first set of analyses explored the pointing errors during adaptation (subjects pointing to left, center or right targets with the visual field displaced to the left or right with prism goggles). Of primary interest was the rate at which pointing error was corrected, the pattern of the pointing errors for the remainder of the 180 trials, and how these were affected by the three independent variables: goggle (left or right), target (fixed or non-fixed) and feedback (hand or indirect) used during the PA (and their combination into 8 different conditions).

3.1.1 Preliminary Exploration

The first analysis was a preliminary exploration of whether expected patterns of error-correction occurred for right and left goggle conditions. The pointing error data were separated by goggle type, collapsed across target and feedback type (separately for each goggle condition), and a mean error score was calculated for each of the 180 trials. These arithmetic mean errors were plotted as a function of trial (Figure 3.1), which revealed the expected pattern of pointing error had occurred for left and right-goggle groups. As displayed in Figure 3.1, initial trials were characterized by large pointing error in the direction of the goggle-induced visual displacement with left-goggle groups displaying left pointing errors (negative values), and right goggle groups displaying right pointing errors (positive values). Subsequently, for both goggle conditions, the mean pointing error rapidly moved towards 0, indicating right and left groups had used accuracy feedback to adjust pointing movements, overcome the displaced visual field, make points relatively accurate (e. g. error correction) in about 15-25 pointing trials.

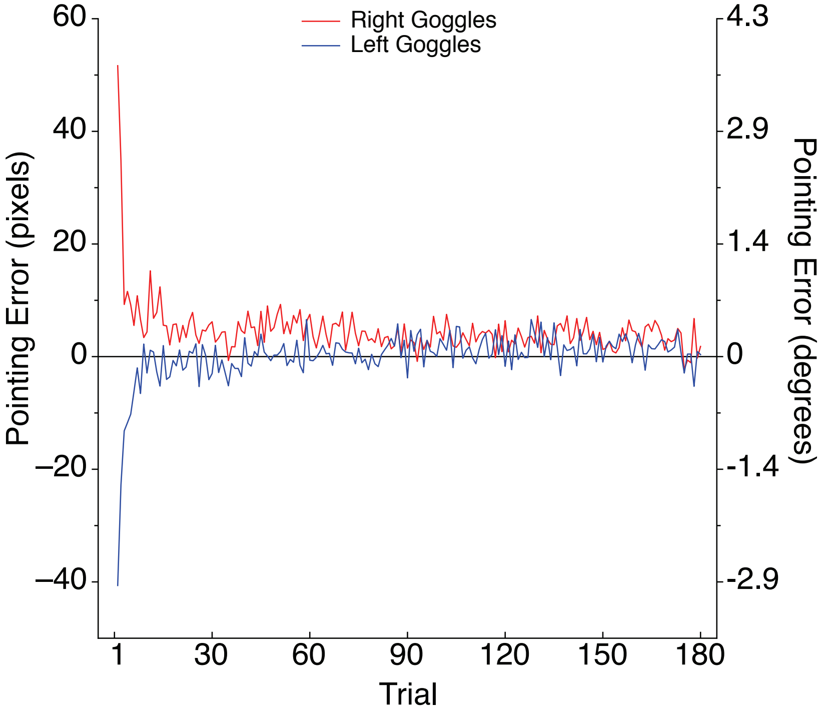

Figure 3.1. Mean pointing error for 180 pointing trials of a Prism Adaptation exercise for Left and Right Goggle groups. Initial points miss targets in the direction of prism-induced visual displacement (positive values indicating right error and negative values left error), and subsequently adjusted points in the opposite direction of the visual shift in order to achieve the intended targets (a process called error correction).

The touch-sensitive VR system recorded points landing to the left-of-center as negative (e. g. initial pointing errors for left-goggles in Figure 3.1), and right-of-center as positive (e. g. initial pointing errors for right goggles in Figure 3.1). In order to make a better comparison of the magnitude and pattern of errors to be made between the two goggle groups pointing errors for left-goggle conditions were mathematically inverted in subsequent analyses and visualizations. Essentially, using this procedure made pointing errors that are relative to the prism direction rather than absolute space[9]. Failure to invert the left-goggle data would result in significant effects of goggle-type by default, and greater difficulty interpreting visualizations of pointing error.

3.1.2 180 Pointing Trials

The second analysis examined how the different combinations of goggle (left or right), feedback (hand or indirect), and target (fixed or non-fixed) affected pointing errors relative to goggle direction when all 180 trials were considered. Pointing errors were submitted to a mixed, repeated-measures ANOVA with goggle and feedback type as the between-subject factors, target type as the within subject factor, and trial (180 pointing trials) as the repeated-measure.

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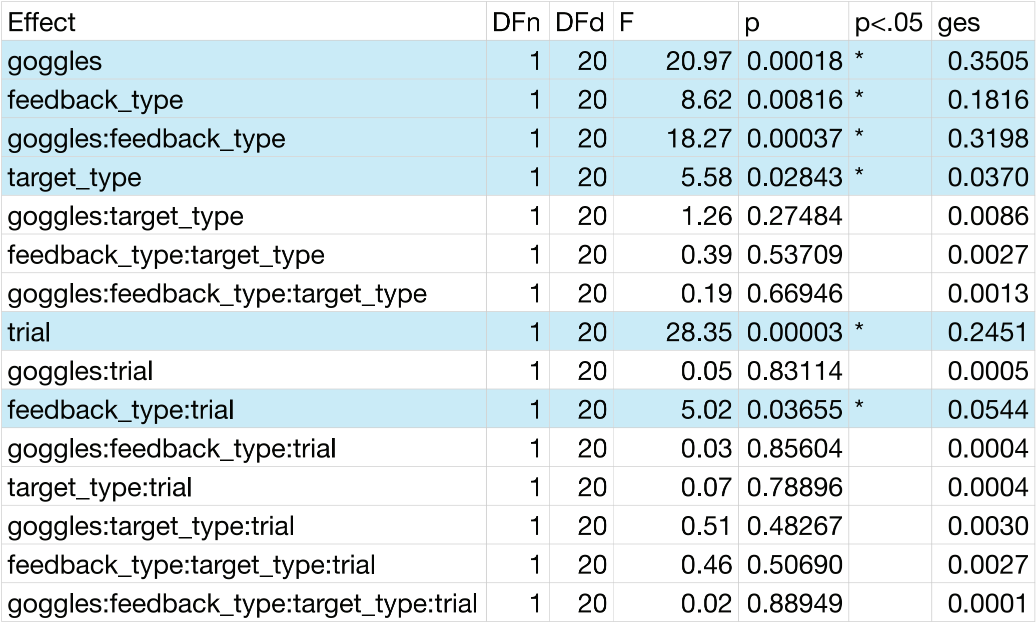
[9] Note that all visualizations of pointing error (with the exception of Figure 3.1 are based on inverted left-goggle adaptation data.

Table 3.1

Output for a mixed, repeated-measures ANOVA on the pointing errors (horizontal distance from visual targets) from 180 trials of Prism Adaptation exercises performed with various combinations of goggles (left and right), targets (fixed and non-fixed) and accuracy feedback (hand or indirect).



Effect	DFn	DFd	F	p	p<.05	ges
goggles	1	20	20.97	0.00018	*	0.3505
feedback_type	1	20	8.62	0.00816	*	0.1816
goggles:feedback_type	1	20	18.27	0.00037	*	0.3198
target_type	1	20	5.58	0.02843	*	0.0370
goggles:target_type	1	20	1.26	0.27484		0.0086
feedback_type:target_type	1	20	0.39	0.53709		0.0027
goggles:feedback_type:target_type	1	20	0.19	0.66946		0.0013
trial	1	20	28.35	0.00003	*	0.2451
goggles:trial	1	20	0.05	0.83114		0.0005
feedback_type:trial	1	20	5.02	0.03655	*	0.0544
goggles:feedback_type:trial	1	20	0.03	0.85604		0.0004
target_type:trial	1	20	0.07	0.78896		0.0004
goggles:target_type:trial	1	20	0.51	0.48267		0.0030
feedback_type:target_type:trial	1	20	0.46	0.50690		0.0027
goggles:feedback_type:target_type:trial	1	20	0.02	0.88949		0.0001

The repeated-measures ANOVA on error scores for 180 trials (Table 3.1) revealed significant effects of goggles, $F(1, 20) =20.97$, $p < 0.00018$, feedback type, $F (1, 20) = 8.62$, $p = 0.008$, target type, $F (1, 20) = 5.58$, $p = 0.03$, and trial, $F (1, 20) = 28.35$, $p = 0.00003$. Significant interactions were found between goggle x feedback type ($F (1, 20) = 18.27$, $p = 0.0037$) and feedback type x trial ($F(1, 20) =5.02$, $p = 0.04$).

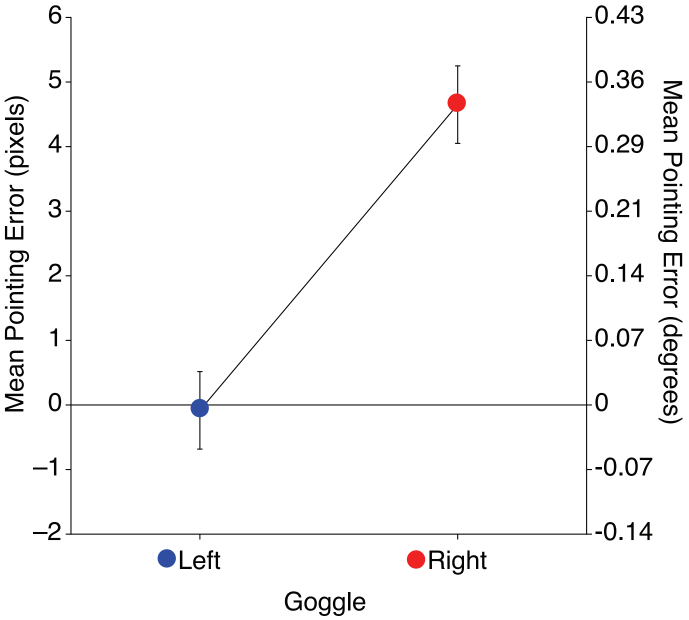


Figure 3.2. Mean pointing error for 180 trials of a Prism Adaptation collapsed across left and right goggle groups.

The main effect of goggles can be described with reference to Figure 3.2, which displays that, across 180 trials, pointing error was larger had been larger for the right-goggle groups (*M*=4.65, *SE*= 0.6 pixels) than the left-goggle groups (*M*= -0.083, *SE*= 0.61 pixels).

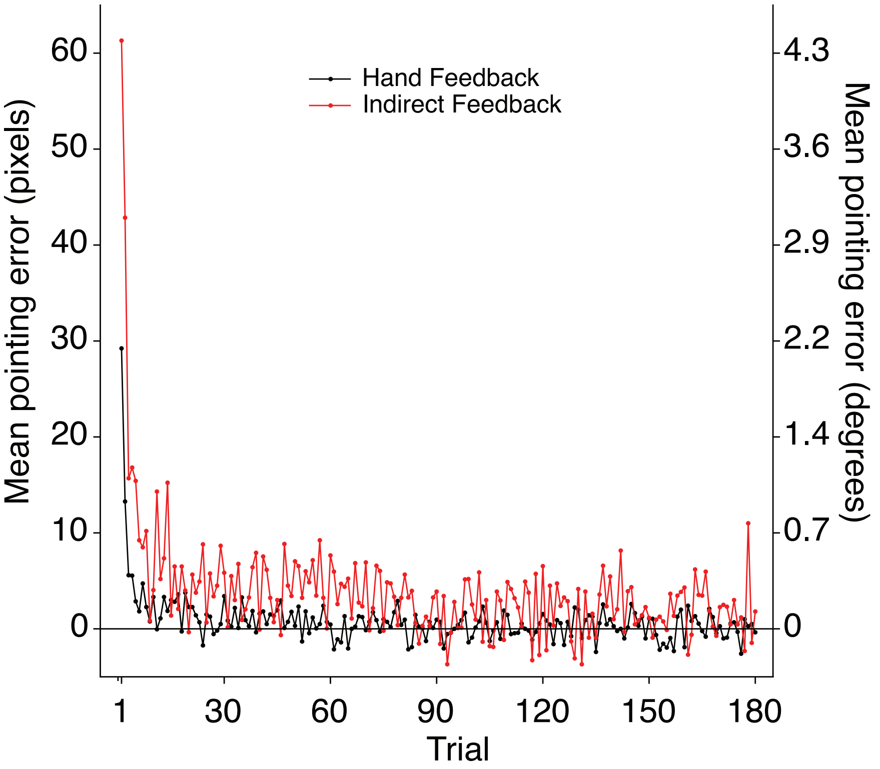


Figure 3.3. Mean pointing error (distance from target) for 180 pointing trials in Prism Adaptation (PA) performed with Hand-feedback (left graph) or Indirect-feedback (right graph) and vision displaced to the left and right.

The main effect of feedback type can be observed in Figure 3. 3 which shows that pointing error in the indirect feedback tended to be larger than with hand-feedback. The main effect of feedback-type was qualified by the feedback-type x trial and goggles x feedback-type interactions. Figure 3.3 displays how the two feedback types differed in the rate at which pointing stabilized and the consistency of pointing in remaining trials. Specifically, the hand feedback exhibited a faster rate of pointing stabilization, followed by consistency (e. g. pointing error displayed very little fluctuation) for the remainder of pointing trials, while the indirect feedback condition exhibited a greater initial error, a more gradual rate of stabilization and greater trial to trial fluctuation thereafter.

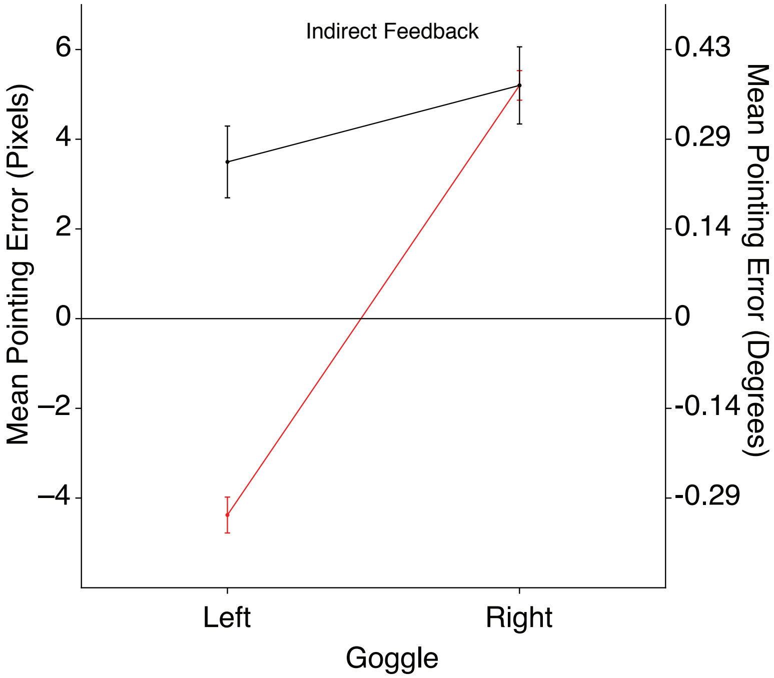


Figure 3.4 Mean error scores collapsed across180 pointing trials during a Prism Adaptation exercise with accuracy feedback provided from the hand or indirectly from a computerized stimulus and vision displaced to the left or right.

Figure 3.4 displays how pointing error differed according to the combination of goggle and feedback-type used during PA. Specifically, there was a difference between the hand and indirect feedback conditions in the left goggle group (*Mdiff*= 7.86 pixels, 0.56 degrees) and no difference within the the right-goggle group (*Mdiff*= 1.1, 0.08). Furthermore, within the left-goggle group, the mean pointing error for the hand-feedback condition was negative (*M*=-4.38 *SE*= 0.40 pixels), while the indirect feedback condition was positive (*M*= 3.49, *SE*= 0.8 pixels), yet in the right-goggle groups, the mean pointing error in both the hand-feedback (*M*=5.20, *SE*= 0.33 pixels) and Indirect-feedback (*M*=4.17, *SE*= 0.86 pixels) were positive. The left goggle group's mean pointing error was negative, which indicates a trend for overcorrection in target pointing (e. g. pointing errors for the left goggle group landed to the right of visual targets), while the positive value of the other conditions indicate a trend for pointing errors were under-corrected (e. g. failure to fully adjust pointing movements in the opposite direction of the goggle shift and make them accurate).

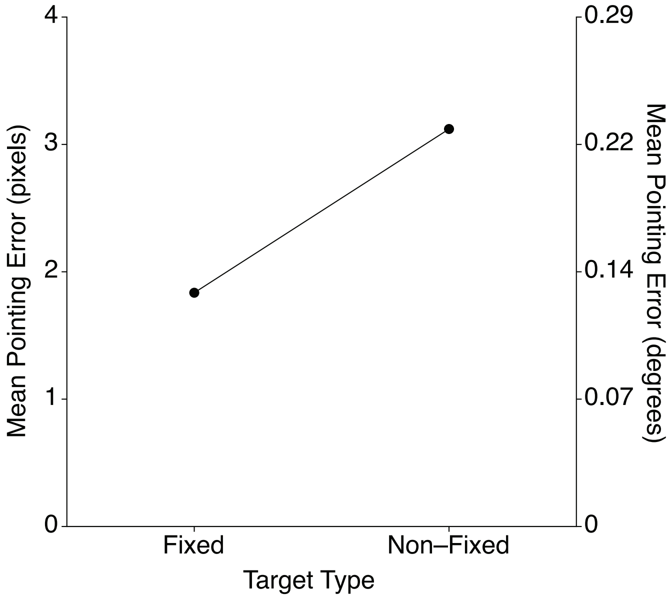


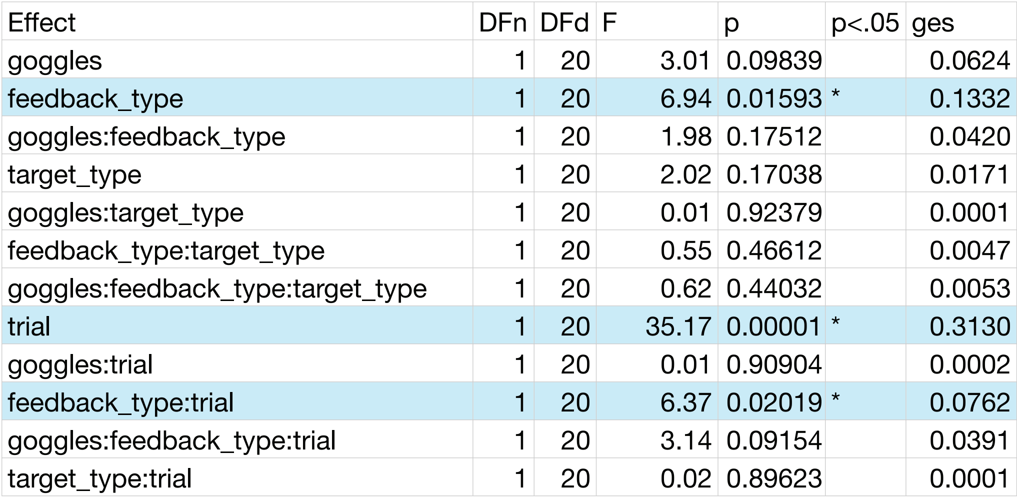
Figure 3.5. Mean pointing errors across 180 pointing of a Prism Adaptation exercise for fixed targets and non-fixed target conditions.

The main effect of target is displayed in Figure 3.5 which shows that pointing error was smaller in the fixed target condition (*M*=1.84, *SE*= 0.19 pixels or *M*=0.13, *SE* = 0.01 deg) than the non-fixed target condition (*M*=3.12, *SE*= 0.21 pixels, *M* = 0.23, *SE*= 0.02 deg).

As illustrated in Figure 3.1 (see also Figure 3.3) stabilization of pointing (as indicated by the decreases and leveling-off of pointing errors) appears to occur within the first 15-25 trials. Based on this observations and the significant trial x feedback interaction, and with the intent of discovering the nature of the main effects of trial and target, two additional analyses were performed that examined how the PA manipulations (goggle, target and feedback type) affected correction of the initial pointing error and performance after pointing stabilized. A mixed, repeated-measures ANOVA (with the same factors of interest as Analysis 3.1.2) was carried out on the error scores from the first 25 pointing trials during the process of error correction (3.1.3). This was repeated on the error scores from trials 26-180 after pointing had appeared to stabilize (3.1.4).

3.1.3 Trials 1-25

Table 3.2.
Output for the repeated measures ANOVA on the error scores (distance from targets) for the first 25 pointing trials of Prism Adaptation performed with various combinations of goggles (left or right), targets (fixed or non-fixed) and accuracy feedback (hand or indirect.



Effect	DFn	DFd	F	p	p<.05	ges
goggles	1	20	3.01	0.09839		0.0624
feedback_type	1	20	6.94	0.01593	*	0.1332
goggles:feedback_type	1	20	1.98	0.17512		0.0420
target_type	1	20	2.02	0.17038		0.0171
goggles:target_type	1	20	0.01	0.92379		0.0001
feedback_type:target_type	1	20	0.55	0.46612		0.0047
goggles:feedback_type:target_type	1	20	0.62	0.44032		0.0053
trial	1	20	35.17	0.00001	*	0.3130
goggles:trial	1	20	0.01	0.90904		0.0002
feedback_type:trial	1	20	6.37	0.02019	*	0.0762
goggles:feedback_type:trial	1	20	3.14	0.09154		0.0391
target_type:trial	1	20	0.02	0.89623		0.0001

The mixed, repeated-measures ANOVA on pointing errors from the first 25 pointing trials (Table 3.2) revealed significant, main effects of feedback type $F(1, 20) = 6.94$, $p = 0.02$ and trial, $F(1, 20) = 35.17$, $p = 0.00001$ that were qualified by a significant feedback type x trial interaction, $F(1, 20) = 6.37$, $p = 0.02$.

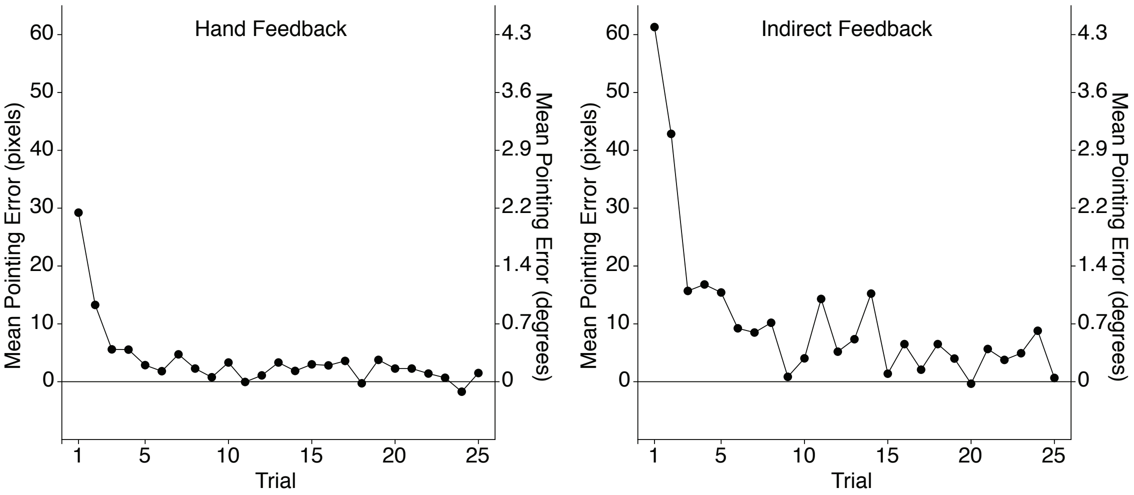


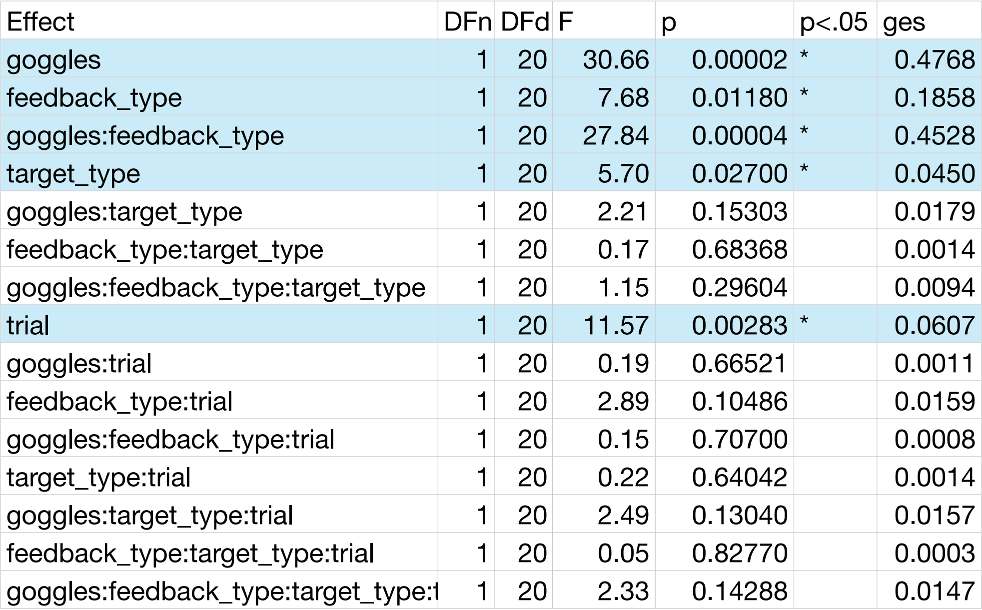
Figure 3.6. Mean pointing error for the first 25 pointing trials of a prism Adaptation exercise performed with accuracy feedback obtained from the hand (left graph) or indirectly from a computerized stimulus (right graph).

The feedback type x trial interaction can be described using Figure 3.6 which displays how the initial pointing error and rate of pointing stabilization differed between hand and indirect feedback types over the course of the first 25 trials. Specifically, in the hand-feedback conditions, the initial pointing errors was smaller and exhibited a faster rate of stabilization (trial 9). In contrast, the indirect feedback condition had a larger Trial 1 error followed by a slower rate of stabilization (trial 15).

It is interesting to note that, unlike the analysis on the error scores from 180 trials (in which a significant effect of target-type had been revealed), no effect or interactions involving goggle or target-type were found on those from the first-25 pointing trials. This suggests left and right goggles and target-type had had differential effects on pointing error after performance stabilized, while having no effect during initial pointing trials (a phenomenon that was confirmed in the 3.1.4 see next section).

3.1.4 Trials 26-180

Table 3.3
Output for the repeated measures ANOVA on the error scores (distance from targets) for pointing trials 26-180 of a Prism Adaptation exercise performed with various combinations of goggles (left or right), targets (fixed or non-fixed) and accuracy feedback (hand or indirect).



Effect	DFn	DFd	F	p	p<.05	ges
goggles	1	20	30.66	0.00002	*	0.4768
feedback_type	1	20	7.68	0.01180	*	0.1858
goggles:feedback_type	1	20	27.84	0.00004	*	0.4528
target_type	1	20	5.70	0.02700	*	0.0450
goggles:target_type	1	20	2.21	0.15303		0.0179
feedback_type:target_type	1	20	0.17	0.68368		0.0014
goggles:feedback_type:target_type	1	20	1.15	0.29604		0.0094
trial	1	20	11.57	0.00283	*	0.0607
goggles:trial	1	20	0.19	0.66521		0.0011
feedback_type:trial	1	20	2.89	0.10486		0.0159
goggles:feedback_type:trial	1	20	0.15	0.70700		0.0008
target_type:trial	1	20	0.22	0.64042		0.0014
goggles:target_type:trial	1	20	2.49	0.13040		0.0157
feedback_type:target_type:trial	1	20	0.05	0.82770		0.0003
goggles:feedback_type:target_type:t	1	20	2.33	0.14288		0.0147

The mixed, repeated-measure ANOVA on pointing errors from trials 26-180 (Table 3.3) revealed significant effects of goggles, *F*(1, 20) = 30.66, *p* = 0.00002, and feedback type, *F*(1, 20) =7.68, *p* = 0.02), target type, *F*(1, 20) = 5.70, *p* = 0.03, and trial, *F*(1, 20) = 11.57, *p* = 0.003. The main effects of goggles and feedback type were qualified by a significant goggle x feedback type interaction , *F*(1, 20) = 27.84, *p* = 0.00004.

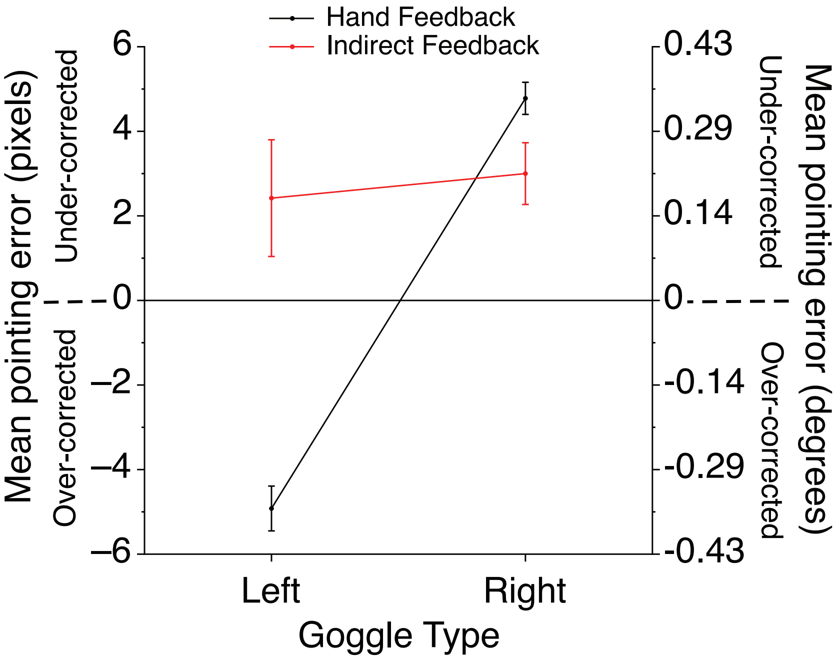


Figure 3.7. Mean error scores after pointing stabilized (trials 26-180) during a Prism Adaptation exercise with accuracy feedback provided from the hand or indirectly from a computerized stimulus and vision displaced to the left or right.

The goggles x feedback interaction for pointing errors of trials 26-180 is illustrated in Figure 3.6, and shows the same effect of goggle and feedback type on pointing error as described for Figure 3.4 in the analysis on 180 trials.

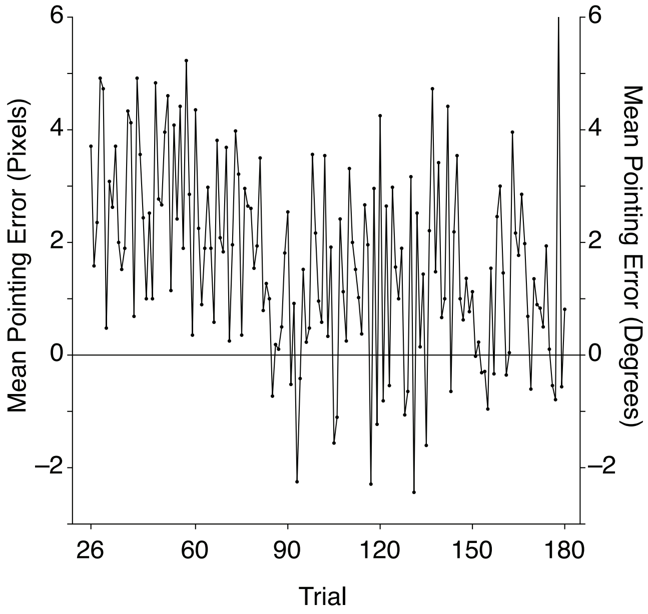


Figure 3.8. Mean error scores for each pointing trial during the stabilized phase (trials 26 - 180) of a prism adaptation exercise. Performance is shown collapsed across goggle (left or right), target (fixed or non-fixed) and feedback (hand or indirect) groups.

The main effect of trial over trials 26-180 is displayed in figure Figure 8. There was a general trend for pointing errors to be larger and under-corrected (positive value) in trials 26-90, and to fluctuate around zero for the remainder of trials (90-180).

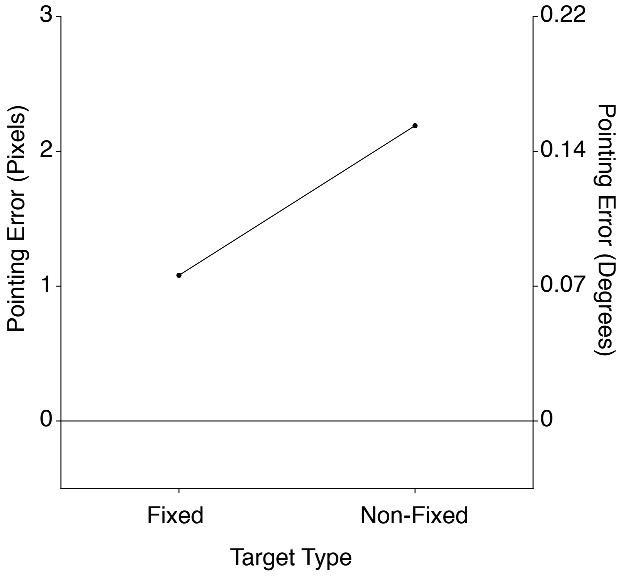


Figure 3.9. Mean error scores after pointing performance stabilized (trials 26-180) during a prism adaptation exercise performed with goggles that displaced the visual field to the right or left, and with fixed or non-fixed targets.

The main effect of target type for pointing trials 26-180 can be explained with reference to Figure 3.9 which shows that the pointing error was smaller in the fixed target condition (*M*= 1.08, *SE* = 0.17 pixels, *M*= 0.08, *SE*= 0.01 degrees) than the non-fixed target condition (*M*= 2.19, *SE*= 0.19 pixels, *M*= 0.16, *SE*= 0.01 degrees).

It is interesting to note that the main effect of target-type and the interaction between goggle and feedback type were significant in the analysis of all 180 trials and in the analysis of trials 26-180 but not in the analysis of trials 1-25. This suggests that these effects were a consequence of mechanisms related to stabilized performance but not during the process of error correction at the early stages of the PA.

3.2 Aftereffect

The aftereffect represents PA effects on the CNS, and is obtained by comparing pre-PA to post-PA performance in one of two types of straight-ahead pointing tasks (SSA or VOL). An aftereffect occurs if, relative to pre-PA, post-PA points shift in the opposite direction of the prismatic displacement of vision experienced during PA (e. g. right-goggles, left aftereffect and vice versa). The aftereffect's magnitude and duration indicates the strength of PA effects with larger and longer aftereffects representative of greater strength.

The following set of analyses was carried out to examine how the various combinations of goggle, target, and feedback type used during PA influenced the magnitude and time-course of SSA and VOL aftereffects. As in previous PA investigations, aftereffects were obtained by subtracting mean pre-PA pointing errors (horizontal distance from the center of the touch-screen) from those in each of the 5, post-PA blocks (hereafter referred to Block 1, Block 2, etc.). Because the computerized PA system recorded points to the left-of-center as negative, right-of-center as positive, aftereffects occurred if difference scores for right goggle conditions were negative values, and those for left-goggle conditions were positive.

One of the main objectives of this investigation was to examine the aftereffect' s strength, as indicated by its magnitude and duration of pre-PA to post PA shifts in the SSA and VOL tasks. In order to make these assessments planned contrasts were carried out, using Fischer's Least Significance Differences (FLSDs), to determine which block displayed a significant pre-PA to post-PA shift for each open-loop task (e. g. a 'significant aftereffect), how long significant aftereffects endured (number of Blocks that remained significant) and when they decayed (aftereffect became non-significant). Specifically, separate FLSD values would be calculated for the SSA and VOL conditions, and these would be placed within an x-y graph (with Block 1-5 on the x axis, and the pre-PA to post-PA difference on the y-axis) above and below a ‘0’, along with the Mean difference scores for Block 1-5. From this we would determine, and illustrate, at alpha =.05 which aftereffects were significantly different from zero.

3.2.1 Independence of SSA and VOL Aftereffects

Aftereffect Analysis 1 (3.2.1) was a carried out to confirm the suggestion made by Sarri et al. (2008) and Ryan (2010) that the SSA and VOL indices are fundamentally different aftereffect measurements. The original (left goggle) and inverted (right goggle) SSA and VOL difference scores were submitted to a mixed, repeated-measures ANOVA with target-type (fixed or non-fixed) and blind (e. g. the open loop tasks, SSA or VOL) as the within-subject factors, goggle (left or right) and feedback type (direct/hand or indirect/indirect) as between-subject factors, and Block (1-5) as the repeated measure. A main effect of blind or significant interactions between blind other factors will be interpreted as evidence that SSA and VOL measures reflect somewhat separable aftereffects.

Table 3.4

Output for a mixed, repeated measures ANOVA on the pre-post PA differences in pointing error in SSA and VOL straight-ahead pointing tasks.

Effect	DFn	DFd	F	p	p <.05	ges
goggles	1	20	12.95	0.00	*	0.1
feedback_type	1	20	0.34	0.56		0.005
goggles:feedback_type	1	20	0.06	0.80		0.001
block	4	80	0.92	0.46		0.004
goggles:block	4	80	2.87	0.03	*	0.01
feedback_type:block	4	80	1.24	0.30		0.006
goggles:feedback_type:block	4	80	2.13	0.08		0.009
blind	1	20	0.05	0.82		0.000
goggles:blind	1	20	0.13	0.73		0.001
feedback_type:blind	1	20	0.46	0.50		0.003
goggles:feedback_type:blind	1	20	0.93	0.35		0.007
target_type	1	20	0.01	0.93		0.0001
goggles:target_type	1	20	0.00	0.96		0.00003
feedback_type:target_type	1	20	0.22	0.65		0.003
goggles:feedback_type:target_type	1	20	1.38	0.25		0.02
block:blind	4	80	0.74	0.57		0.003
goggles:block:blind	4	80	3.88	0.01	*	0.02
feedback_type:block:blind	4	80	0.66	0.62		0.003
goggles:feedback_type:block:blind	4	80	2.82	0.03	*	0.01
block:target_type	4	80	0.92	0.45		0.002
goggles:block:target_type	4	80	1.20	0.32		0.003
feedback_type:block:target_type	4	80	0.04	1.00		0.0001
goggles:feedback_type:block:target_type	4	80	1.02	0.40		0.003
blind:target_type	1	20	0.11	0.75		0.0004
goggles:blind:target_type	1	20	0.02	0.88		0.0001
feedback_type:blind:target_type	1	20	1.38	0.25		0.006

The mixed, repeated-measures ANOVA on SSA and VOL difference scores (Table 3.4) revealed a significant effect of goggles (F(1,20) = 12.95, p = 0.002) and significant interactions between goggle x block (F(4,80) = 2.87, p = 0.03), goggles x block x blind (F(4,80) = 3.88, p = 0.006), and goggles x feedback type x block x blind (F(4,80) = 2.81, p = 0.03).

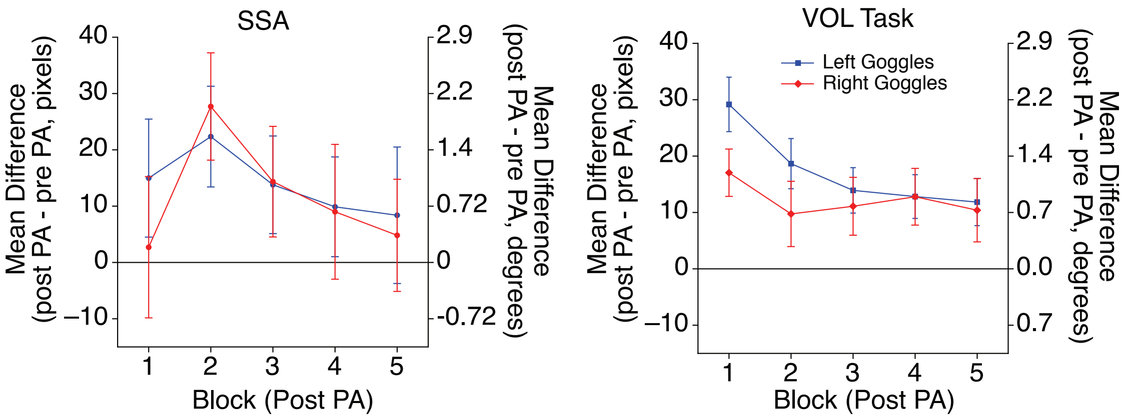


Figure 3.10. The time-course of the aftereffect for 40-minutes following a computerized prism adaptation (PA) exercise performed with accuracy feedback from the hand (left graph) or indirectly from a computerized stimulus (right graph), and the visual field displaced to the right or left. The aftereffect, an index of PA-induced modification to the central nervous system, is represented by differences scores calculated from the performance of open-loop pointing tasks (measured as the horizontal distance from objective straight-ahead) performed in five, post-PA blocks relative to one, pre-PA block. Error bars represent +/- 1 Standard Error.

Because of the two interactions involving the method of measuring the aftereffect (blind), and the clear differences between the time course of the two tasks' aftereffects displayed in Figure 3.10, before further discussion we will conduct separate ANOVAs on the SSA and VOL scores.

3.2.2. SSA

To investigate the effects of goggles, feedback type, and target type on SSA aftereffects, difference scores (relative to goggle direction) were submitted to a mixed, repeated-measures ANOVA with target-type (fixed or non-fixed) as the within-subject factors, goggles (left or right) and feedback type (hand or indirect) as between-subject factors, and block (1-5) as the repeated measure.

Table 3.5
Output for a mixed, repeated measures ANOVA on the pre-PA to post PA difference scores of a subjective straight ahead (SSA) pointing task.

Effect	DFn	DFd	F	p	p<.05	ges
goggles	1	20	4.66	0.04	*	0.08
feedback_type	1	20	0.49	0.49		0.01
goggles:feedback_type	1	20	0.08	0.78		0.00
block	4	80	0.65	0.63		0.01
goggles:block	4	80	2.53	0.05	*	0.02
feedback_type:block	4	80	0.83	0.51		0.01
goggles:feedback_type:block	4	80	2.60	0.04	*	0.02
target_type	1	20	0.01	0.94		0.00
goggles:target_type	1	20	0.01	0.92		0.00
feedback_type:target_type	1	20	0.03	0.87		0.00
goggles:feedback_type:target_type	1	20	2.71	0.12		0.04
block:target_type	4	80	1.48	0.22		0.01
goggles:block:target_type	4	80	0.90	0.47		0.01
feedback_type:block:target_type	4	80	0.09	0.98		0.00
goggles:feedback_type:block:target_type	4	80	0.99	0.42		0.01

The mixed, repeated-measures ANOVA on SSA difference score (Table 3.5) revealed a significant effect of goggles ($F(1,20) = 4.66$, $p = 0.04$), and interactions between goggle x block ($F(4, 80) = 2.53$, $p = 0.05$) and goggle x feedback-type x block ($F(4,80) = 2.60$, $p = 0.04$).

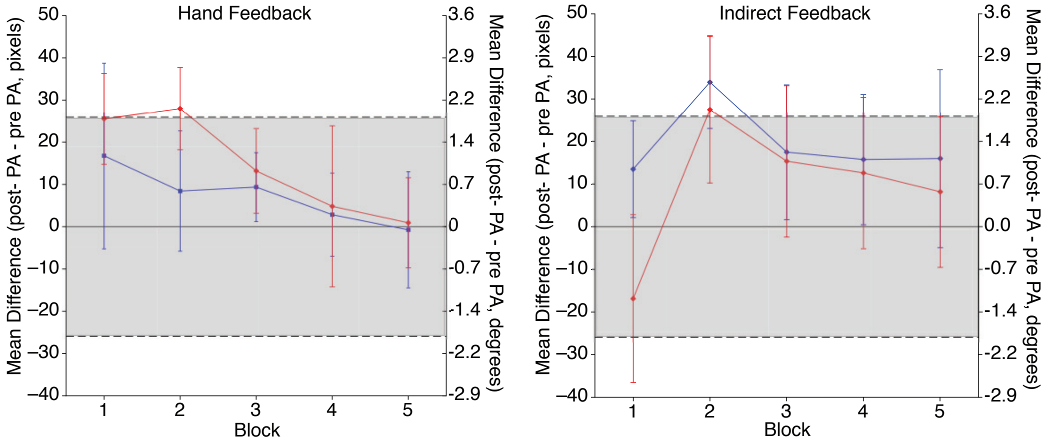


Figure 3.11. The time-course of the aftereffect of a subjective-straight ahead (SSA) pointing task for 40-minutes after prism adaptation (PA) Aftereffects are significantly different from zero when the scores fall outside the shaded region (defined by the FLSD, see text).

Overall, Figure 3.11 displays that SSA aftereffects following computerized PA were non-significant for the majority of blocks for both goggle groups (indicated by the mean difference scores falling within the FLSD region). In the few cases where the aftereffects were significant, they appeared at relatively short latencies following PA (Block 1 or 2), and were transient-(always decayed by Block 3). The main effect of goggles, and the goggle x block interaction were qualified by the 3-way interaction between goggle x feedback type x block. The three-way interaction can be observed in how the left and right goggle aftereffects differ between hand and indirect feedback conditions within the first two blocks of open loop pointing (Figure 3.11). In the first two blocks of the hand-feedback condition, the SSA aftereffect was significant for right-goggles, but not left-goggles. Alternatively, in the indirect-feedback condition, a delayed-onset aftereffect in Block 2 for both left and right goggle groups.

3.2.3 VOL

To investigate the effects of goggles, feedback type, and target type on VOL aftereffects, Analysis 3.2.2 was repeated with VOL difference scores.

Table 3.6.
Output for a mixed, repeated measures ANOVA on the pre-PA to post PA difference scores of a visual open-loop (VOL) pointing task

Effect	DFn	DFd	F	p	p<.05	ges
goggles	1	20	22.29	<0.001	*	0.35
feedback_type	1	20	0.01	0.91		0.00
goggles:feedback_type	1	20	1.37	0.26		0.03
block	4	80	3.12	0.02	*	0.01
goggles:block	4	80	13.85	<0.001	*	0.04
feedback_type:block	4	80	2.74	0.03	*	0.01
goggles:feedback_type:block	4	80	0.59	0.67		0.00
target_type	1	20	0.12	0.73		0.00
goggles:target_type	1	20	0.00	0.96		0.00
feedback_type:target_type	1	20	1.98	0.17		0.04
goggles:feedback_type:target_type	1	20	0.00	1.00		0.00
block:target_type	4	80	1.20	0.32		0.00
goggles:block:target_type	4	80	1.97	0.11		0.00
feedback_type:block:target_type	4	80	0.21	0.93		0.00
goggles:feedback_type:block:target_type	4	80	0.24	0.91		0.00

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The mixed, repeated-measures ANOVA on VOL difference score (Table 3.6) revealed significant effects of goggles ($F(1,20) = 22.29$, $p < 0.001$), block ($F(4,80) = 3.12$, $p < 0.02$) and interactions between goggle x block ($F(4, 80) = 13.85$, $p < 0.001$) and feedback-type x block ($F(4,80) = 2.74$, $p = 0.03$).

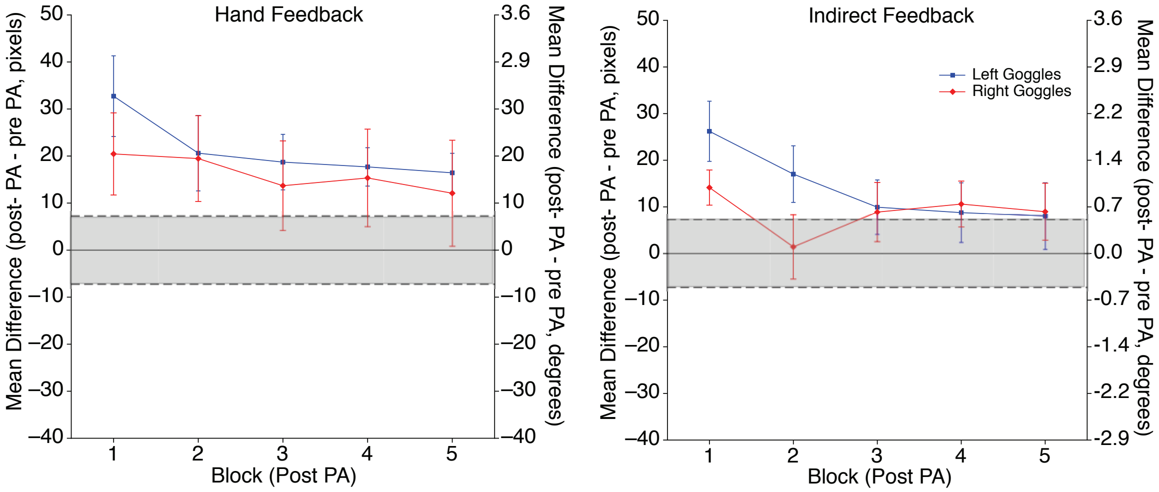

Figure 3.12. The time-course of the aftereffect of a visual open-loop (VOL) pointing task for 40-minutes after prism adaptation (PA) Aftereffects are significantly different from zero when the scores fall outside the shaded region (defined by the FLSD, see text).

As displayed in Figure 3.12, when there was a difference due to goggle, the aftereffect was larger with left goggles. This is a reflection of the main effect of goggle. For both feedback conditions the aftereffect was largest in Block 1, and tended to decline in Block 2-5. This is a reflection of the main effect of Block. Importantly, using this measure of the aftereffect, it was still significant 40-minutes after PA (mean differences above the FLSD region in Block 5). However, reflecting the 2-way interaction between block and goggle and block and feedback, the rate and pattern of the aftereffect's time course displayed notable differences between the hand and indirect feedback-types, as well as the right and left goggle groups.

From Figure 3.12, the goggle x block interaction can be explained by the tendency for the aftereffects to be larger for left-goggle groups than right goggle groups in early Blocks (e. g. Block 1 and Block 2), but for the between-goggle difference to disappear in later Blocks (e. g. aftereffects take on similar magnitudes Block 3-5).

The feedback-type x block interaction resulted from differences between the hand-feedback and indirect feedback conditions' aftereffect magnitude and rate of decay over the course of Block 1-5. Figure 3.12 shows that in hand-feedback conditions the aftereffects tended to be of larger-magnitude, displayed a gradual decay rate over Block 1-5, and were still clearly significant and stable in later Blocks (e. g. mean difference scores are clearly above the FLSD region in Block 3-5). In contrast, aftereffects following indirect feedback tended to be of smaller-magnitude, show an immediate and rapid decay rate after Block 1, and were barely significant in the later Blocks (e. g. Block 3-5).

3.2.4 Results Summary

Adaptation was measured using three indices; pointing errors over the course of the 180-trial PA exercise (otherwise known as adaptation), and two aftereffect indices (SSA and VOL pointing). Performance patterns that emerged in each will now be summarized.

3.2.4.1 Adaptation

In a preliminary assessment of pointing errors two distinct 'phases' of adaptation emerged (Figure 3.2 and 3.3). Prior to trial 25 an 'error correction' phase took place in which trial 1 errors and leftward or rightward adjustments occurred as expected in each goggle group (Figure 3.1). This was followed by a 'stabilized' phase between trials 25 and 180 in which pointing error was relatively consistent (Figure 3.1, 3.13 and 3.14).

There were notable differences between the hand and indirect feedback conditions during this 'error correction' phase (Figure 3.6). Specifically, compared to the indirect-feedback condition, pointing with hand-feedback had a smaller initial pointing error, displayed a faster rate of stabilization, and less trial-to trial variability in remaining trials (Figure 3.6).

Although pointing error was similar for left and right goggle groups during the error-correction phase, during the stabilization phase (trials 26-180) there were significant effects of the combination of goggles and feedback type. Surprisingly, during this later stage none of the groups had completely and accurately adapted to the goggles (Figure 3.7). For both feedback conditions in the right-goggle group and for the indirect feedback condition of the left goggle group pointing stabilized with an ‘under-correction’ bias. In the remaining condition, pointing in the left-goggle/hand feedback group pointing stabilized with an ‘over-correction’ bias .

The combination of goggles and feedback type were not the only factors that influenced pointing performance. An interesting pattern was revealed when target-type differences were found to affect pointing during the ‘stabilized’ phase (Trials 26 - 180), but not during initial pointing adjustment (‘error correction’ phase, Trials 1-25). Specifically, subjects were more accurate when pointing towards fixed targets than non-fixed targets (Figure .

3.2.4.2 Aftereffect

The SSA aftereffects were generally unreliable for all combinations of feedback and goggle type (Figure 3.12). The few significant aftereffects that *did* occur were in the expected directions (e. g. right-goggle, left aftereffect and vice versa), but were of small magnitude and short-duration (e. g. Block 1 and 2 of the right-goggle/hand-feedback condition), or delayed-onset and transient (right and left goggle groups in Block 2 of the indirect feedback condition). In all cases the aftereffects decayed prior to Block 3 (20 minutes post-PA) and remained at pre-PA levels for the last two blocks.

In early blocks, pre PA to post PA change in SSA performance varied according to the specific combination of goggle and feedback type (Figure 3.12). Following PA with hand-feedback, the SSA points made within 10-minutes following PA (Block 1 and 2) displayed a small-magnitude aftereffect for right-goggle groups, and were larger than left-goggle groups for whom pointing did *not* show reliable changes. Following indirect feedback PA, although neither right or left goggle groups exhibited a significant aftereffect in Block 1 (in which the right-goggle displayed an unexpected, non-significant trend for a right aftereffect), both displayed delayed-onset aftereffect (expected directions) 10-minutes post-PA (Block 2). In addition, in contrast to the hand-feedback task, the aftereffect was slightly larger for left than right goggle-groups. Thereafter, SSA pointing returned back to pre-PA levels by 20-minutes post-PA (Block 3) and remained there for the duration of Blocks (Block 4 and 5).

VOL aftereffects were durable following PA with all combinations of goggle and feedback (Figure 3.13). Aftereffects for right and left goggle groups were in expected direction, and lasted at least 40-minutes post-PA (Block 5). Over the course of 5 Blocks, aftereffects were larger following hand feedback PA. Within each feedback group aftereffects tended to be larger for left goggles than right goggles in early blocks; a difference that disappeared as the aftereffect decayed, and pointing exhibited its expected return to pre-PA levels (right and left goggle groups exhibiting similar performance in Block 3-5).

Finally, despite that pointing performance had differed between fixed and non-fixed targets during the ‘stabilized’ phase of adaptation, the factor was not found to influence characteristics of the aftereffect.

3.2.4.3 Adaptation-Aftereffect Comparison

Given that aftereffects are likely caused by processes that are engaged during the adaptation phase, but that the relationship between adaptation and the aftereffect is not well-defined, it was necessary to examine how performance during PA carried over to SSA and VOL performance following PA. With the intent of gaining insights into possible relationships between the two stages, a side-by-side comparison of the adaptation and aftereffect characteristics will be made for all combinations of goggle and feedback. As in previous analyses, SSA and VOL will be considered separately.

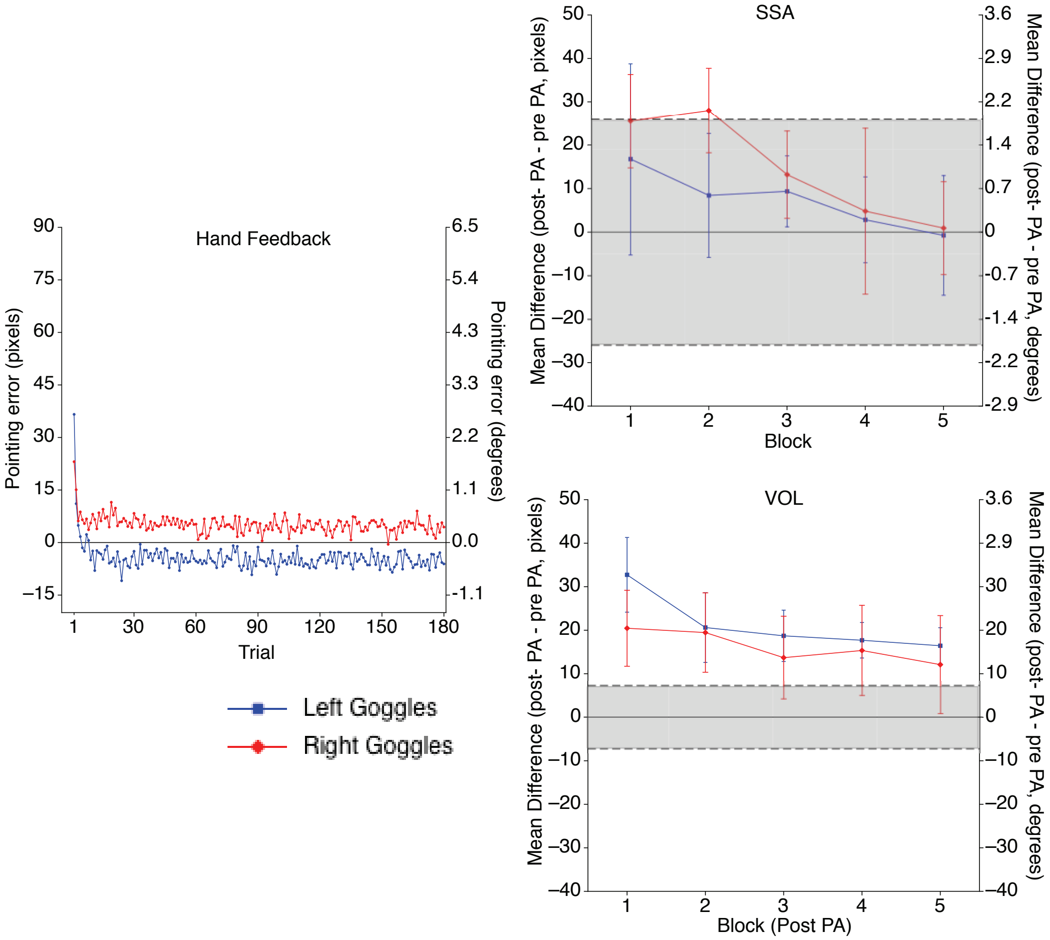

Figure 3.13. Side-by-side comparison of the adaptation and the SSA (top right) and VOL (bottom right) aftereffects for left and right goggle groups in the hand-feedback condition.

The adaptation and aftereffect data from the hand-feedback groups are shown in Figure 3.13. Here it can be seen that between goggle differences in the stabilized phase of adaptation (also see Figure 3.7) appear to translate into between-goggle differences in the aftereffects.

Right goggle-groups did not fully-adjust points, and maintained an ‘under-corrected’ bias during this phase. In the open-loop tasks that followed, SSA aftereffects were of small magnitude and short duration (10 minutes, Block 1 and 2), while VOL aftereffects were initially small (relative to left-goggle groups; Block 1), but displayed minimal decay over 40 minutes (still significant at Block 5). In contrast, the left-goggle group stabilized at a slower rate (trial 10), adjusted points beyond full error correction, and maintained this ‘overcorrection’ bias over remaining trials. In open-loop tasks that followed, SSA performance did not show significant aftereffects, yet the VOL aftereffects that emerged were of relatively large magnitude in Block 1, and decayed rapidly to similar levels of the right-goggle groups in Block 2-5.

Thus,in the hand-feedback condition, the relative correction bias when pointing stabilized had short-term, but *not* long-term, carry over to VOL aftereffects. Specifically, under-corrected points during PA (right goggle-group) lead to smaller VOL aftereffects than over-corrected points (left-goggle groups which had a larger aftereffect) in Block 1. Yet, between-goggle differences during adaptation did not impact later VOL aftereffects (Block 2-5), which had similar magnitude for left and right goggle groups.

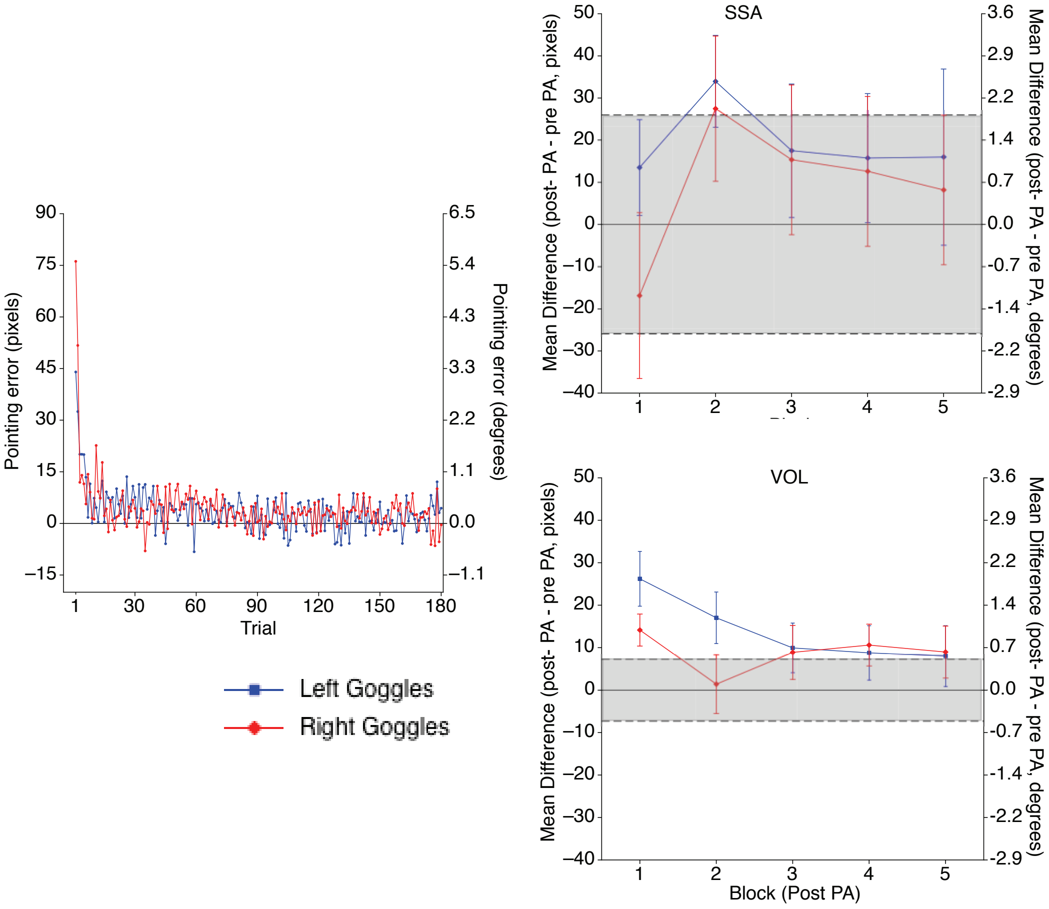

Figure 3.14. Side-by-side comparison of the adaptation and the SSA (top right) and VOL (bottom right) aftereffects for left and right goggle groups in the indirect-feedback condition.

In the indirect-feedback condition (Figure 3.14), the overall pattern in the ‘error correction’ phase of adaptation was similar for left and right goggle groups throughout error-correction and stabilized phases of adaptation. In contrast to the hand-feedback condition, pointing error in the stabilized phase for left and right goggle groups had been under corrected (Figure 3.7 and 3.14) and, as displayed in Figure 3.14, characterized by a high rate of trial to trial fluctuation. The similarities in goggle groups’ adaptation were followed by similar SSA aftereffects that had a small magnitude, delayed onset, and short duration (appearing weakly in Block 2 failing to remain significant thereafter). In contrast, goggle groups’ similar adaptation was followed by VOL aftereffects that were larger for left goggles in Block 1 and 2, while showing a similar-sized, slow-decaying aftereffect from 20 - 40 minutes in the remaining blocks.

Thus, when both goggle groups failed to fully correct pointing error and performance showing fluctuation from trial-to-trial during the stabilized phase of adaptation the weak SSA aftereffect that emerged was also similar for left-goggle and right-goggle groups. In contrast, although early-VOL aftereffects showed between-goggle differences, the small-magnitude aftereffects at longer durations were characterized by similarity.

When adaptation-to-aftereffect performance for left and right goggle groups is compared between the two feedback conditions, it appears that the performance during the ‘stabilized’ phase results in between-condition differences in VOL aftereffects, but not SSA aftereffects.

Hand feedback conditions were characterized by consistent over-correction (left-goggle) or under-correction (right-goggle) biases linked to goggle direction. This consistent performance was followed by strong VOL aftereffects that were larger in magnitude (than those following adaptation with indirect feedback) over the course of all post PA blocks (and were still going strong at least 40-minutes post PA). In comparison, when the indirect feedback groups exhibited variable performance (fluctuated slightly above and below the targets) during the stabilized phase, the VOL aftereffects that followed were of smaller-magnitude in Block 1-5, and had almost returned back to pre-PA levels after 40-minutes. In contrast, regardless of the speed or consistency during adaptation, the SSA aftereffects in both feedback-groups, if occurring at all, were small of magnitude, appeared in early blocks (Block 1 and/or 2), and always decayed before 20-minutes (Block 3).

Chapter 4 Discussion

In this final section the adaptation and aftereffect results will be discussed and interpreted in terms of their support for, or disconfirmation of the hypotheses that had been developed prior to the investigation. Factors that may have lead to curious findings will be identified, and suggestions will be made for how future investigations can fill these gaps. Findings will also be compared to those from previous computerized-PA investigations, traditional PA literature, and suggestions made their application for research that attempts to ameliorate unilateral neglect.

The current study was designed for eventual use with patients. As such, hypotheses that had been developed concerning adaptation and aftereffects were based on findings and theories from the neglect-patient PA literature (e. g. Sarri et al., 2008, Serino et al., 2006 and 2007), as well as on reports of the induction of neglect-like behavior in healthy subjects (Berberovic & Mattingly, 2003; Colent et al., 2000; Michel 2006). Admittedly, prior to undertaking the investigation, the author had paid little attention to the extensive literature exploring PA effects in healthy subjects. However, although it came somewhat retrospectively, the healthy-normal, non-neglect studies (and in particular those of Redding & Wallace) ended up being useful for placing some of the current study's unexpected results into context. Since the discussion will make reference to a widely-accepted theory of PA from the normal literature about the processes that occur during adaptation that were not detailed explicitly in the introduction, they will be explained briefly now, and elaborated upon when specific results are discussed.

Redding et al. (2006) explain PA in the context of motor control theory, and specifically, how visual and proprioceptive reference frames (which can be thought of as maps within the CNS that are used to interpret sensory information and control movements) are adapted by PA. During an eye-hand pointing task (such as PA), targets are initially coded in the visual reference frame (centered in the head). This information is included in a movement plan (developed in the motor control centers) that specifies a path the limb must take to achieve the intended target. The movement plan is relayed to the proprioceptive system (centered in the shoulder for the pointing limb), which guides the pointing movement within its reference frame.

Successful eye-hand movements depend on the state of "alignment" between the visual and proprioceptive reference frames within a 'common reference frame' (known as the 'noetic nexus' and thought to be contained in the cerebellum, see Redding et al., 2005 and Redding & Wallace, 2006). When visual information must be used by proprioception during coordinated hand-eye movements, an adjustment is made in the noetic frame that accounts for the constant, horizontal distance between the head and shoulder[10] (and that is based on each systems coded position in the noetic frame).

In PA, when goggles displace the visual reference frame (and all content within), targets appear to the *right* or *left* of their true location. Thus, the movement plan is based on the displaced target information. During initial adaptation trials, the adjustment of target information (from vision, and for use by proprioception) is based on 'normal'

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[10] To clarify, during a right-handed pointing task, if a target is located at subject midline it falls in the middle of the visual reference frame (centered in the head), but to the left-of-middle within proprioceptive reference frame (shoulder-centered). In visual calibration, the target is coded in the center of the reference frame, and 'target-center' information is incorporated into a feedforward motor command. If the 'target-center' information was not adjusted prior to proprioceptive calibration the right limb would be directed to the middle of its shoulder-centered reference frame, and the hand would be carried to the right of the target. However, when alignment adjusts for the lateral distance between the head and shoulder the point is directed toward the target.

alignment (distance between the head and shoulder); and the resultant point is guided to the right or left of the target (in the direction of the goggle shift). Internalized detection of the discordance between the visual and proprioceptive feedback sets off a signal that the systems are ‘misaligned’, and two mechanisms are engaged to bring the reference-frames back into alignment (Bedford, 1993).

The first of the mechanisms is known as ‘recalibration’ (strategic control [11]): a side-pointing strategy that subjects deploy to quickly correct initial pointing errors. During the process, the movement plan is quickly readjusted in the opposite direction of goggle displacement until accuracy is achieved, yet the visual and proprioceptive reference frames maintain their normal state of alignment (based on the constant distance between the head and shoulder). In healthy normals, this recalibration occurs within the first 10-15 pointing trials ; and is typically followed by stable performance in remaining trials (Redding & Wallace, 1993; Berberovic & Mattingley, 2003).

The second process, known as ‘realignment’, occurs with continued target-pointing. It is slower to develop, and is characterized by ‘perceptual learning’ in which visual and proprioceptive reference frames gradually establish a new state of alignment (e. g. coded positions in the noetic frame) based on the displaced visual reference frame and proprioception. Although the exact time it occurs is uncertain, realignment is thought to occur sometime after pointing stabilizes. It is also necessary for the development of

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11 In this context strategic control refers to a class of motor control processes that allow common, coordinated actions that make use of multiple sensory systems (e. g. vision and proprioception) that serve perceptual-motor behavior (e.g., Paillard, 1991; Grobstein, 1988; Sparks, 1988). Instances of such strategic control include task-specific deployment of visual guidance, predictive feedforward control, conscious error-correction based from feedback that is consciously perceived , performance changes based on internalized knowledge of results.

aftereffects, and may also be critical for inducing amelioration of neglect in patients (Redding & Wallace, 1993; Redding et al., 2005; Redding & Wallace, 2006).

Adaptation

The two phases of adaptation ('error correction' and 'stabilized') are temporally consistent with two adaptive processes that operate during PA (Redding et al., 2005; Redding & Wallace, 2006). The 'error correction' phase (trials 1 - 25) corresponds with the process of 'recalibration'; while the 'stabilized phase' corresponds to when 'realignment' likely occurs.

As expected, error correction (or recalibration) was prompted by large-magnitude pointing errors in trial 1 (Figure 3.1). However, trial 1 error was not uniform across the PA conditions. As reported, hand-feedback conditions exhibited a smaller-magnitude pointing error than indirect-feedback conditions (Figure 3. 6.). Both feedback conditions exhibited a first-trial effect in which trial 1 error is typically shown to be less than the expected displacement of the visual displacement. While the indirect feedback condition's initial errors were within range of 40-70 % of goggle shift that have been reported in previous healthy-normal investigations (Redding & Wallace, 1993, 2003; Redding et al., 2005), those for the hand-feedback condition were more accurate than what would be expected (approximately 2 degrees, Figure 3.6).

Trial 1 error was likely smaller in the hand-feedback conditions because, when the hand appeared midway through the point to the left or right of its expected location, this appearance would likely have motivated subjects to slow down the movement, make an 'online' correction to the movement plan, and thereby reduce pointing error. The initial pointing error was larger for the indirect-feedback condition because the hand was invisible for the duration of the pointing movement. Consequently, with indirect feedback there would be no benefit and therefore not motivation to slow down the pointing movements. To confirm whether on-line correction was a factor in the first trial effects, analysis of movement time would be required. Unfortunately, this was not a factor originally considered in the current investigation.

After trial-1 error, adjustments in pointing began to occur as expected (e. g. shift in the opposite direction of visual displacement), and exhibited patterns that were both consistent and inconsistent with those reported previously in the healthy-normal PA literature. PA conditions stabilized around the expected rate of 10-15 trials (Redding et al., 2005; Redding & Wallace, 2006). However, the faster stabilization in hand-feedback conditions (> trial 10) relative to indirect-feedback conditions (trial 16) does not agree with findings from Clower & Boussaoud (2000), that these two feedback conditions demonstrate a similar rate of pointing adjustment with both stabilizing within 10 trials (Clower & Boussaoud, 2000).

As hypothesized, Left and right-goggle groups exhibited similar pointing performance during the error correction phase (no significant effect of goggles during trials 1-25). Following the initial error, the hand-feedback condition displayed a faster rate of adjustment (stabilized at trial 9) than the indirect feedback condition (trial 15).

It had been anticipated that all PA conditions would bring points into alignment with targets, and stay there for the remainder of pointing trials, yet the results revealed otherwise. During the stabilized phase of the hand-feedback conditions (both goggle groups), points consistently landed to the right of targets (Figure 3.7 and 3.13), while those in the indirect-feedback condition failed to fully correct pointing error (Figure 3.7) and displayed a high rate of trial-to-trial fluctuation to the left or right of targets (3.14). These patterns contrast those of previous computerized PA studies that reported complete correction of pointing error (e. g. adjusted limb movements until points were aligned with targets) in left-goggle (Clower & Boussaoud, 2000), right goggle PA (Wilms &Mala, 2010)[12], and for both hand and indirect feedback types.

In the current study, the right-biases within the hand-feedback conditions were particularly curious because they represented different 'types' of inaccuracy for the left and right goggle groups. For the right-goggle group the bias was an 'under-correction' because points had not been fully adjusted leftwards. In the left-goggle group the bias was an 'overcorrection' because rightward adjustments in pointing had continued beyond target achievement; a pattern that will become important later when explaining the aftereffects that correspond to these two PA conditions.

To this author's knowledge, under-corrected pointing has not been reported previously in healthy-normal subjects. On the contrary, over-correction has been reported in an investigation by Redding and Wallace (1993) The over-correction during the current-study's error-correction phase (Trials 26-180) overlapped temporally the same phenomenon reported previously (which occurred occurred between pointing trials 20-40) Overcorrection is believed to take place when side-pointing strategy deployed during early pointing trials (that quickly correct initial pointing errors) persist as

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[12] Although Wilms &Mala (2010) did not thoroughly investigate characteristics of the pointing error during adaptation (focus was placed on comparison of the aftereffect between traditional and computerized PA), it was reported that subjects successfully corrected pointing error in all PA protocols.

realignment of the visual and proprioceptive reference frames develop (Redding & Wallace, 1993 and 2006; Redding et al., 2005).

The under-corrected pointing error is likely an unknown artifact of the computerized-PA procedure. Although the factors underlying the biases unknown, whatever the mechanism may be (and assuming the cause was not alteration of attention and space representation), it was surprising that subjects did not employ a strategy to make points accurate, especially after explicit instructions to 'use feedback to make points accurate' and repeatedly seeing the hand miss the targets.

One of the primary goals of this investigation was to examine possible effects of target type on adaptation performance. Specifically, given apparent differences in cognitive load between fixed-target PA (larger cognitive load) and non-fixed target PA (smaller cognitive load), and evidence that increased cognitive load impairs the process of adaption (Redding & Wallace, 1985), in the fixed-target condition it had been expected that subjects might have experienced greater difficulty adapting to prisms, and this would be indicated by a slower rate of error correction. Contrary to this hypothesis, pointing performance did not differ between the fixed and non-fixed target conditions during the 'error correction' phase (pointing trials 1-25). This finding suggests that if there was a difference in cognitive load between fixed-targets and non-fixed targets, it did *not* affect initial adjustments in pointing.

There are several possible reasons for the null effect of target-type during the 'error correction' phase. It is possible that the difference in cognitive-load between fixed and non-fixed targets is not as large as hypothesized, or at least not enough to cause performance to vary. In addition, perhaps the strategic process of quickly adjusting points (e. g. fast adjustment of movement plan) to correct for previous pointing error (e. g. recalibration) overshadows, minimizes or masks effects of cognitive-load differences of the targets. Finally, given the simplicity of both fixed and non-fixed target procedures, it remains possible that, contrary to my hypothesis, there is not a between-goggle difference in cognitive load, and thus, the ease at which 'error-correction' occurs would not be expected to differ.

In addition, the non-significant findings about target-type effects on error correction may be a case where the observed behavior in healthy normals can not be extended to unilateral patients. Pointing performance during error correction precedes the time when PA induces plastic changes in the CNS (such as induction of neglect). Thus, the pointing errors during this time reflect how a 'non-injured' brain is processing targets, and not how an injured brain might. During the error-correction stage of traditional PA investigations, healthy subjects do not experience difficulties making full correction of pointing error (Redding et al., 2005). However, as evidenced in the investigation by Serino et al. (2006 and 2007), not all patients are able to correct pointing error, and those who do not also fail to show amelioration of PA following the exercise. Thus, effects of target type and how it may or may not affect error correction during PA (and subsequent amelioration of neglect) in patients is still a topic that merits further investigation.

However, target-type *did* affect pointing error in the 'stabilized' phase (trials 26 - 180), when pointing performance in the fixed-target condition were more accurate than those in the non-fixed target condition (Figure 3.9).

The significant effect of target-type during the 'stabilized' phase of adaptation is important because it suggests subjects were processing fixed and non-fixed targets differently at the time corresponding to the process of 'realignment'(which may be critical for PA-induced amelioration of neglect in patients). Aftereffects

It was assumed that during adaptation, the visual and proprioceptive systems had been exercised, and the degree that PA had modified the systems would be represented by the magnitude and duration of SSA and VOL aftereffects. Specifically, any SSA aftereffects would be interpreted as effects on internal representation of straight ahead and proprioceptive guidance(e. g. the felt position of the hand towards perceived straight ahead), while VOL aftereffects would be attributed to changes in vision and proprioception. General expectations included that aftereffects would occur in the opposite direction of the goggle-type used during PA (right-goggle, left-aftereffect), be larger immediately following PA, and show decay back to pre-PA levels over the course of 40-minutes (in which five blocks of SSA and VOL pointing were performed). In addition, the relative strength of PA effects for the eight combinations of google, target and feedback would be revealed by their aftereffect's magnitude and duration (with larger and longer-lasting aftereffects indication stronger PA effects).

Across all PA conditions, SSA aftereffects appeared early, had a small-magnitude and decayed within 20 minutes or did not occur at all. These results indicate that, regardless of the combination of goggle, feedback, or target-type, computerized-PA had induced weak modifications to internal representation of straight-ahead and the proprioceptive system, or no modification at all. The results are contrary to original expectations that, because SSA is a more sensitive measure measure of neglect-related phenomena (Sarri et al., 2008), and that left-goggle PA induces neglect-like behavior in healthy-subjects (Michel, 2006), SSA aftereffects would be stronger than VOL aftereffects in left-goggle conditions (which, as will be described next, was not the case).

All PA conditions displayed VOL aftereffects that endured for at least 40-minutes, but were larger following hand-feedback than indirect-feedback at all time periods. The VOL aftereffects indicate that effects of hand-feedback had been stronger (Figure 3.13). On one hand, these findings agree with two previous computerized PA-investigations (Clower & Boussaoud, 2000; Wilms & Mala, 2010) in that hand-feedback produced larger VOL aftereffects than indirect feedback. Alternatively, there is some dissimilarity between this study and its predecessors in that, although the aftereffect following indirect conditions were smaller, they were still reliable.

The largest VOL aftereffects emerged immediately after PA, and were followed by gradual decay towards pre-PA levels; a pattern that was consistent with original expectations and consistent with other investigations that have studies time-course characteristics of the aftereffect (e. g. Fernandez-Ruiz & Diaz, 1999; Fernandez-Ruiz, 2004). Interestingly, within each feedback condition, early VOL aftereffects (0-10 minutes post-PA) were larger in the left goggle group (exhibiting the expected right-shift in pointing) than right-goggle group (exhibiting the expected left-shift in pointing); a pattern that indicates the computerized PA conditions may have induced neglect-like behavior similar to that described in Michel (2006). However, at least in the hand-feedback conditions, the early VOL aftereffects may not be entirely due to an induction of neglect but, at least partially, the result of motor patterns that had carried over adaptation. Regardless of the underlying source of the between-goggle difference, the finding countered the original prediction that, even if left-goggles induced neglect-like behavior, VOL aftereffects would be similar for left and right goggle groups; a hypothesis based on evidence that the relationship between the visual and proprioceptive systems is unaffected by neglect [13] (Sarri et al., 2008 and Redding & Wallace, 2006), and that healthy-normal and neglect patients tend to show similar VOL aftereffects (Sarri et al., 2008), and thus, the unseen hand can still be used to guide the hand toward the visual target.

As the initial, large-magnitude VOL aftereffects decayed, the difference between right and left goggle groups disappeared and displayed a similar magnitudes from 20-minutes onwards. Thus, according to the suggestion by Fernandez-Ruiz et al. (2004) that ‘true’ aftereffects occur at longer post-PA latencies (and after an initial decay of large-magnitude ones), even though stronger effects shortly after PA for left-goggles, the ‘true’ aftereffects may have been similar for left and right goggle groups.

When looking at the aftereffect results as a whole, those measured by SSA were completely contrary to expectations, and VOL aftereffects were mixed. Some of the unexpected findings can be traced back to specific components of the PA set-up and characteristics of adaptation performance that may have altered the typical changes PA induces in the visual and proprioceptive systems. This, in turn may have been carried over to the performance of SSA and VOL tasks. In addition, the relatively small sample in each PA condition may have prevented significant effects from being observed.

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[13] Neglect patients can still make goal-directed hand movements within right-space.

Information from the healthy-normal literature can be used to help place some of the unexpected aftereffects into context. The original hypotheses were derived from literature that dealt with PA effects on neglect patients and the induction of neglect in healthy-subjects, but essentially ignored the extensive research carried out with healthy subjects. Alas, it may have been an ignorance of the healthy-normal literature that lead to oversights in experimental methodology and gaps in the results. For example, unlike the neglect-patient literature, in which either SSA *or* VOL pointing is used to quantify aftereffects, many of healthy-subject investigations employ *three* aftereffect tests: SSA pointing for proprioceptive aftereffects, a 'visual aftereffect' in which subjects position a target 'straight ahead' without using the hands, and VOL as a 'total aftereffect' that is the sum of visual and proprioceptive aftereffects. If all three measures of the aftereffect had been collected in the current investigation, the extent to which PA conditions had modified vision and proprioception in isolation or combined would have been immediately apparent, and we might have been able to discern how much of the total VOL measurement was due to extraneous sources.

The unexpected finding that VOL aftereffects were larger and longer lasting, while SSA aftereffects were absent or weak may have arisen from factors that minimized proprioceptive modification during adaptation, yet still induced visual aftereffects. The first factor, which was observed subjectively by the experimenter, was that the right hand was brought towards the visual targets (both during error correction and after performance stabilized) through angular rotation of the trunk rather than an isolated arm movement guided by proprioception. In addition to rotational movement, the lack of change in proprioception (SSA) that followed indirect feedback PA, may have have come about because of the ‘terminal’ nature of performance feedback; which has been shown to primarily induce changes in vision but not proprioception (Redding & Wallace, 1992).

During PA (and open-loop tasks), subjects pointed toward the touch screen with full body and head movement permitted. This posture was similar to the study of Wilms &Mala (2010), but differed from Clower & Boussaoud (2000) and the majority of PA investigations that use a chin-rest and/or head restraint (pictured in Figure 1.1) to keep subjects’ head and body aligned and centered with respect to targets (adaptation) or objective straight ahead (open-loop pointing)pointing tasks (Ryan, 2010). A postural bias was not expected to be a concern in healthy subjects, and so the restraints were intentionally omitted. However, as was discovered post-hoc, the restraints also function to minimize rotational movement of the trunk during adaptation and open-loop pointing tasks. Although such rotational movement was not quantified in the experiment, the experimenter also noticed that it was more pronounced in some subjects than others. Thus, at least for the subjects who adopted a rotational motor pattern to adjust points closer[14] to the targets (rather abducting or adducting the right arm), the proprioceptive system may not have been adapted (e. g. maintained its normal state of alignment with vision). This may explain why the system did not show reliable post-PA change (as reflected in SSA performance).

Another possible explanation for the absence of proprioceptive aftereffects in the indirect-feedback condition may be the timing at which performance feedback became

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[14] The phrase ‘closer to targets’ is used here rather than ‘pointing was accurate’ because of the consistent inaccuracies in performance in the hand-feedback conditions. However, even this inaccurate performance was closer to the targets than large, trial-1 errors.

available during adaptation. Based on findings from Redding & Wallace (1992), when accuracy feedback during PA is 'terminal' (e. g. hand is not visible until the end of the movement), aftereffects are primarily visual (e. g. in the hands-free placement task subjects will typically place a target to the left or right of center, and in the direction of the goggle-displacement), and those in proprioception are minimal[15]. In the current investigation, although the hand was never explicitly available to vision during indirect-feedback PA, the appearance of the vertical line on the touch screen was not available until the *termination* of the pointing movement. From this vantage point, the weak or absent SSA aftereffects that followed indirect-feedback conditions are *consistent* with investigations that have reported minimal proprioceptive aftereffects following terminal-feedback PA with healthy subjects.

The total aftereffect (VOL) is the sum of visual and proprioceptive aftereffects. Therefore, whether it was terminal-feedback, or rotational movement that resulted in minimal proprioceptive modification (and weak or absent SSA aftereffects), it can be hypothesized that the VOL aftereffects represent pure *visual* aftereffects. In order to test if PA effects are mostly visual following unrestrained, late-feedback and/or both conditions, the current study would need to be repeated with the inclusion of a 'visual' centering task.

Regardless of the relative contributions of vision or proprioception, the durable VOL aftereffects that followed PA with hand and indirect-feedback differ from the two

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[15] When feedback becomes available early in the movement during adaptation, aftereffects are mostly proprioceptive (SSA points shift in the *opposite* direction of the goggle shift), while visual aftereffects are minimal. In PA when the hand becomes visible midway through the point, similar-sized visual and proprioceptive aftereffects are found (but in opposite directions). The relative amount of adaptation in each system varies as a function of how early or late feedback becomes available.

previous computerized PA investigations reporting VOL aftereffects following indirect feedback were weak or unreliable compared to hand-feedback (Clower & Boussaoud, 2000; Wilms &Mala, 2010). In both previous studies there was an absence of aftereffects, and it was explained that this may have occurred because the indirect feedback PA failed to fulfill the conditions of the object unity assumption (Welch, 1972; Welch & Warren, 1980). When applied to PA, the assumption states that accuracy-feedback must be represented in the visual and proprioceptive systems as coming from the same object in extrinsic space (e. g. the hand or the computerized stimuli). This common representation is required for discordance detection (e. g. perception that visual and proprioceptive systems are misaligned), and subsequent realignment. The authors contended that the computerized feedback that represented pointing error may have attributed to the external environment rather than physically coincident with the hand (which could not be seen beneath the occlusion board). Furthermore, although strategic adjustments allowed for successful adjustment of pointing error to achieve the intended targets, because discordance detection had not occurred, realignment of visual and/or proprioceptive systems did not take place, and VOL aftereffects were weak or absent (Clower & Boussaoud, 2000; Wilms &Mala, 2010).

Assuming the validity of the object unity proposal, I can explain my discrepant finding (small but reliable and durable VOL aftereffects) by the further assumption that the larger number of pointing trials in the current study (180) compared to Clower & Boussaoud (2010) (50) and Wilms & Mala (2010) (90), allowed more time for object unity to be established (e. g. feedback representation within the visual and proprioceptive systems). This explanation is supported by non-computerized PA studies, that report after-effect strength depends on the number of limb movements are made (as opposed to the amount of time goggles are worn), and where more practice results in stronger aftereffects (Prablanc et al., 1975; Fernandez-Ruiz & Diaz, 1999).

The VOL aftereffects resemble the two-stages of aftereffects proposed by Fernandez-Ruiz et al. (2004). Both feedback conditions (and particularly the hand-feedback condition), displayed large-magnitude aftereffects from 0-10 minutes post-PA. These were followed by smaller-magnitude aftereffects that showed gradual decay from 10 - 40 minutes. The early-VOL aftereffects, which were disproportionately larger for left-goggle than right-goggles conditions, may represent induction of neglect-like biases, the first time such a phenomenon has been observed using computerized PA. Although a right aftereffect was found following left-goggle PA in Clower & Boussaoud (2000), that study did not include a right-goggle comparison group that could have been used to determine whether the two goggle types had induced differential effects.

However, for the hand-feedback condition, neglect-induction may not be the only explanation for the VOL pattern. Instead, these ‘early’ aftereffects may represent short-term motor memory that had carried-over from the recent adaptation task. Figure 3.13 and 3.14 display that during adaptation with hand-feedback the majority (94 - 98%) of trials had been characterized by over-correction or under-correction biases. The straight-forward relationship appeared as follows. During the stabilized phase of adaptation, left-goggle groups demonstrated a consistent, large-magnitude right-shift in pointing (over-correcting pointing error, see Figure 3.7), which was followed by a VOL aftereffect that was large-magnitude, and rightward (Figure 3.13). In contrast, during the stabilized phase of adaptation the right-goggle group demonstrated a consistent, small-magnitude left shift in pointing (under-correcting pointing error, Figure 3.7 and 3.13), which was followed by a VOL aftereffect was small-magnitude and leftward (3.13). These hand-feedback results are similar to healthy-subject investigations that have shown continuity in pointing performance from adaptation performance to aftereffects. For example, when subjects must adjust points further to the left or right in order to correct for a larger displacement of the visual field (e. g. larger goggle shift), larger aftereffects emerge. Furthermore, in a similar manner to the left-goggle/hand-feedback condition, it has been shown that over-correction during adaptation produces larger-magnitude aftereffects than complete correction of error (Redding & Wallace, 1990, 1992, 1993, 1994).

For the indirect-feedback condition, the between-goggle difference in the VOL aftereffect can not be attributed to an effect of short-term motor memory that carried over from adaptation, because goggle groups had shown similar patterns of pointing error through error-correction and stabilization phases of the exercise (Figure 3.14). Thus, the early, between-goggle indirect-feedback results likely indicate a neglect-like bias, and given the absence on a proprioceptive aftereffect (SSA), the effect was likely occurred in the visual system.

Whether the early between-goggle differences had been due to motor memory or neglect induction, the effect was short-lived regardless of feedback type. In line with the second-stage of the aftereffect proposed by Fernandez-Ruiz et al. (2004), following initial, large-magnitude aftereffects, both aftereffects in both feedback conditions were small and demonstrated a gradual rate of decay from 10-40 minutes post-PA. In addition, as described above, during this time period, the between-goggle difference in aftereffects had disappeared.

In the hand-feedback condition, if early aftereffects (large magnitude, and between goggle difference) represent motor-memory, carry-over from adaptation, and later aftereffects represent the ‘true’ modification to the CNS (Fernandez-Ruiz et al., 2004), the VOL aftereffects found between 10-40 minutes indicate that hand-feedback PA with left and right goggles had modified the CNS with similar strength. This is an interesting concept, given the over-or-under correction biases during adaptation. If it is assumed that late VOL aftereffects are representative of PA effects on the ‘visual’ system (given that Visual = VOL - SSA, and where SSA aftereffects were weak or absent), the results suggest that the similar visual modifications had occurred regardless of whether pointing errors during adaptation had been under-corrected (right goggle) or an over-corrected (left goggle) (Figure 3.7 and 3.13).

With regard to the indirect feedback condition, under the assumption that the large between-goggle difference in the early VOL aftereffects was due to induction of neglect in the left-goggle group, the convergence of right and left goggle aftereffects (10-40 minutes) suggests that this was a short-lived effect. Furthermore, the effect’s transience was only revealed because of the repeated measurements of the open-loop tasks (e. g. five blocks over the course of 40 minutes after PA). If the study had been modeled after earlier computerized PA investigations and only tracked aftereffects immediately (<10 minutes) following PA, the longer-term similarities between the left and right goggle groups would have been missed. With regard to investigations into the aftereffect, our method speaks to the importance of tracking both the magnitude and duration of effects, as opposed to taking single open-loop measurements before and after PA. Without repeated measurements a full picture of the time course of modifications would not have been obtained.

Final Thoughts

The current study took advantage of touch-sensitive technology that automatically presented auditory cues, visual targets and collected pointing data in an attempt to delineate the specific effects of PA performed with left or right-shift goggles, fixed or non-fixed targets and hand or indirect feedback on characteristics of adaptation and two-types of aftereffects (SSA and VOL).

In the two previous renditions of computerized-PA (Clower & Boussaoud, 2000; Wilms &Mala, 2010), which also investigated differences between hand and indirect-feedback, the strength of PA effects were interpreted based on immediate VOL aftereffects that followed brief adaptation periods (50 and 90 pointing trials) with either right or left shifting goggles. As a result of extensions made to the preceding studies, several novel findings were obtained in the current investigation.

The first extension to the previous investigations was the equal attention paid to characteristics of the aftereffect and adaptation. In the quest to identify the PA's underlying mechanisms and amelioration of neglect, the relationship between adaptation and aftereffects should not be overlooked. This is because PA-induced changes (whether open-loop pointing or more complex cognitive processes) are ultimately stimulated by the preceding visuomotor task. In the current study comparing the adaptation and aftereffect (Figure 3.13 and 3.14) , allowed for some insight into how various patterns of adaptation (e. g. over-correction, under-correction, or accuracy in pointing, Figure 3.7 and 3.14) did (or did not) carry-over to the aftereffect (e. g. no change in SSA, early vs. late magnitude of the VOL aftereffects) in the various PA conditions.

The study's inclusion of right *and* left goggle conditions provided evidence of neglect-like behavior in healthy subjects, the first time the effect has been reported using computerized-PA. This was indicated by disproportionately large, VOL aftereffects that occurred in the first 10-minutes following left-goggle PA. Based on suggestions by Michel (2006), this is probably evidence that computerized PA modified the mechanisms underlying neglect. However, a key word here is *preliminary*. As will be discussed in greater detail below, further computerized-PA investigations that use left and right goggle groups must be carried out to determine if the neglect-like effect on VOL pointing extends to cognitive tasks that use systems that are *not* directly involved in the adaptation procedure (e. g. VOL makes use of both vision and proprioception).

Compared to previous investigations, the current study used a larger number of a adaptation trials and a more extensive measurement of the aftereffect of adaptation. The number of adaptation trials (180), was at least 2-3 times that of previous investigations, which lead to strong modifications in the CNS (e. g. VOL aftereffects for at least 40-minutes post PA). Furthermore, I suspect it was likely the increase in practice that stimulated the VOL aftereffects following PA with indirect-feedback condition, which had not shown reliable aftereffects in previous investigations. This result may provide preliminary evidence that, when performing PA under conditions where an element of disconnect is present (e. g. when healthy subjects have trouble directly relating feedback to the physical act of pointing, or when patients experience problems making necessary error correction), larger amounts of practice may be necessary to establish the appropriate connections and facilitate plastic changes in the CNS (e. g. reliable aftereffect in healthy subjects and amelioration of neglect in patients).

In typical studies that examine PA effects in patients suffering from unilateral neglect and that explore neglect-induction in healthy normal participants feedback during PA comes from the hand at the midpoint of the movement's trajectory (Ryan, 2010). However, the finding of a neglect-like bias in the early VOL aftereffects following 'terminal' feedback may have useful applications for neglect-related PA research. To this author's knowledge a thorough investigation of how the timing of feedback may affect the underlying mechanisms and central deficits of neglect has not been carried out. Is it possible that amelioration of the specific neglect symptoms varies as a function of when feedback is provided, in a similar manner to the amount of realignment in the visual and proprioceptive systems in healthy-subjects? For example, perhaps right-biases in visual attention (e. g. visual search and perception of chimeric faces) that have often shown an inconsistent response to PA (Ferber, Dankert, Joanisse, Goltz, & Goodale, 2003; Morris, Kritikos, Berberovic, Pisella, Chambers, & Mattingley, 2004; Sarri, Kalra, Greenwood, & Driver, 2006; Saevarsson, Kristjansson, Hildebrandt, & Halsband, 2009; Vangkilde & Habekost, 2010; Ryan, 2010) have come about as the result of timing of feedback that did not induce enough modifications to the visual modality. It would be interesting to see whether more reliable results would be obtained in visual tasks that follow PA with terminal feedback. Timing of feedback and its effects on a wide range of neglect-related deficits remains a topic to be explored with both healthy-normal and neglect patient subjects. Finally, although it is beyond the scope of the current investigation, it has been suggested that neglect amelioration is more reliable following multiple dose interventions than single-dose studies, perhaps due to the role of practice in establishing and reinforcing beneficial connections (see Ryan, 2010).

. Successive observations of the aftereffect allowed for a more complete picture of the aftereffect's time course, as opposed to the single 'snap-shot' of immediate PA effects. The multiple measurements of the aftereffect revealed the transient nature of the neglect-like VOL aftereffect; as indicated by the disappearance of the between-goggle difference. The pattern gives a preliminary indication of the 'window of opportunity' future researchers may have for measuring neglect-like behavior of more complex attention and space representation processes, which will be discussed in greater detail below.

Along with the strengths of the current investigation, there are also weaknesses. Consequently, if the experiment were to be repeated I would recommend several changes to the study's procedure and experimental manipulations.

During pointing tasks more care would be taken to control participant's posture and encourage pointing and pointing correction to be made with the adduction or abduction of the arm rather than rotational movement of the trunk. As is typical in neglect-patient PA studies, subjects would perform pointing tasks seated in an upright position (rather than standing) with the head restrained and/or in a chin rest (see Figure

1.1). It is expected that with posture restrained, pointing with the arm will be guided by proprioceptive system (rather than 'brought' to the target by way of trunk rotation), and SSA aftereffects are likely to emerge; indicative of PA-induced change in proprioceptive system (a similar hypothesis to that stated at the outset of this investigation).

Given the large number of PA manipulations in the current study (2 goggle and 2 feedback as between-subject factors and 2 target-types as within-subject factor), if it was repeated it would be impractical to include an additional PA manipulation of 'posture' (e. g. restrained vs. unrestrained). However, the effect of posture on adaptation and aftereffects may be an interesting area for future investigations to explore, and could reveal if unrestrained posture indirectly leads to visual but not proprioceptive aftereffects. Such an investigation could also be expanded to include kinematic movement analysis of trunk and limb movements (e. g. Hodges, , Cresswell, & Thorstensson, 1999) during the restrained vs. unrestrained conditions. This may provide some insight into how much angular movement of the trunk contributes to the correction of pointing error and what (if any) role this plays in the relative strength of visual and proprioceptive aftereffects, and (in if a left vs. right goggle condition is incorporated) in the induction of neglect-like behavior. With respect to the last point, this may provide data on how important pointing with the arm is for stimulating neglect's underlying mechanisms.

A visual centering task would be added to the SSA (proprioceptive) and VOL (total= visual + proprioceptive) aftereffect indices. Thus, rather than relying on indirect measure of the visual aftereffects (visual = VOL - SSA), the PA-induced changes to the visual system would be observed directly.

During the error correction phase there was uncertainty about why the initial (trial 1) pointing error was smaller in hand-feedback than indirect-feedback conditions. It was suspected that sight of the hand may have prompted subjects to slow down the pointing movement and make an 'online' corrections. To test whether this was the case, movement time would be added as a factor of interest. Furthermore, since it is already known that there is an optimal pointing cadence for the development of aftereffects (Redding & Wallace, 1990), an assessment of movement time throughout the course of adaptation may also provide useful information about how pointing speed during adaptation is affected by different experimental manipulations (e. g. goggle, target, feedback type) and also how pointing speed and these manipulations may interact to modify the aftereffect.

A curious result concerns the was the over-correction (left-goggle group) and under-correction (right-goggle group) that occurred in the hand feedback condition when pointing had stabilized during adaptation (trials 26-180, see Figure 3.7 and 3.13). While the source of the over-correction bias has been described previously (Redding & Wallace, 2005 and 2006), the under-correction bias does not seem to have a basis.

Finally, there were only 5, 6 or 7 participants in each subgroup (see Appendix A). Although, among the effects I hypothesized might occur, there were not many marginal ones in the expected direction, it would still be recommended that future investigations use larger sample sizes. If combined with the suggestions of better control of posture, increasing the number of subjects would greatly increase the power to observe effects. In turn, significant effects (such as the VOL aftereffects) that *were* found would likely be stronger, and effects that may have masked by due to variability introduced by experimental and subject factors could emerge. In particular, I expect that reliable SSA aftereffects would likely emerge in the hand-feedback conditions.

With the increased availability of touch-sensitive technology, computerized PA is likely to see increased use for research purposes, both with healthy-normals and neglect-patient subjects. The current study lays a solid foundation on which subsequent computerized-PA investigations can be based. The next step will be to use similar technology to investigate how PA factors of target-type, and feedback type (and possibly posture, target-location, and movement time) modify more complex attention and space representation processes.

During the ‘stabilized phase’ of adaptation, pointing error had differed between the fixed vs. non-fixed target conditions, with pointing exhibiting greater accuracy in the fixed target condition (Figure 3.9). This result suggests that the two targets were being processed differently during the time in adaptation when most plastic changes in the brain likely occur (‘realignment’). Despite this, there was no effect of target-type on the aftereffects. It is important to keep in mind that, besides possible differences in cognitive load, target-types may also differ in the specific type of attention drawn (e. g. endogenous for fixed targets vs. exogenous for non-fixed targets), and vary in the amount of conflict resolution required in generating a response, and both show characteristic impairments in neglect patients (Bartolomeo & Chokron, 2001; Losier and Klein, 2001; Chica, de Schotten, Toba, Malhotra, Lupianez, & Bartomomeo, in press) and vary in their response to PA (Streimer and Danckert, 2007; Nijboer, McIntosh, Nys, Dijkerman & Milner, 2008; Schindler, McIntosh, Cassidy, Birchall, Benson, Ietswaart, & Milner, 2009). Thus, although SSA and VOL aftereffects were unaffected by target type, the same may have not been the case if attentional orienting or conflict resolution tasks, both of which appear to share similar processing features with the fixed and/or non-fixed target-types, had been administered.

It is likely that studies will continue using healthy-subjects to explore the mechanisms underlying unilateral neglect and its amelioration following PA. In such cases, the aim will be to design and/or incorporate tests that measure cognitive processes while a 'neglect-like' state is still induced. Although the aftereffect has shown a different rate of decay than other cognitive tasks (e. g. (Pisella et al., 2002, Frassinetti et al., 2002; Serino et al. 2006 and 2007), it may still provide a rough estimate of the 'window of opportunity' for observing neglect-like effects in healthy normals. Based on the current study, the 'window' likely is within the first 10-minutes post-PA. So that important results will not be missed it will be important to identify and/or design tests of the appropriate length such that PA effects do not decay before tests are completed.

Although much of this discussion has focussed on the application of healthy-normal results, the importance of starting to use computerized-PA with patients should not be overlooked. From this study's results, computerized PA is likely stimulating the same mechanisms as traditional forms. Furthermore, the advantages that the technology affords with regards to stimulus presentation and performance recording will undoubtedly be useful for direct exploration of PA's target and feedback-type effects in patients. All of this study's strengths, weaknesses (and ways to overcome them), and the future directions apply equally to explorations patients. While it is not necessary to carry out exploration of goggle-type with patients (patients do not show cognitive effects from right-shifting goggles), the manipulations of target and feedback on aftereffects and higher-level cognitive processes should begin immediately. Patient and healthy-normal investigations need not be carried out independently of one another, because the information gained from *both* healthy-normal and neglect-patient PA investigations can and will be useful for putting all of the pieces of the PA-puzzle (e. g. its underlying mechanisms and its amelioration of neglect) together.

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Appendix A- Demographic Information

Demographic information, assigned experimental condition and order, and standing distance from the touch screen apparatus of the 24 subjects completing two sessions of prism adaptation.

ID	Age (yrs)	Sex m=male f=female	Dominant Hand (r= right, l=left)	Experimental Condition^a and Order		Distance from touchscreen (cm)
				Session 1	Session 2	
6	24	f	r	LG FT HF	LG NFT HF	67
23	25	f	r	LG FT HF	LG NFT HF	72
24	18	f	r	LG FT HF	LG NFT HF	72
11	25	m	r	LG NFT HF	LG FT HF	72
16	20	f	r	LG NFT HF	LG FT HF	79
5	22	f	r	LG FT IF	LG NFT IF	73
17	26	f	r	LG FT IF	LG NFT IF	67
2	21	f	r	LG NFT IF	LG FT IF	67
10	23	m	r	LG NFT IF	LG FT IF	70
13	23	m	r	LG NFT IF	LG FT IF	75
20	27	f	r	LG NFT IF	LG FT IF	68
1	28	f	r	RG FT HF	RG NFT HF	79
4	24	f	r	RG FT HF	RG NFT HF	69
18	21	f	r	RG FT HF	RG NFT HF	76
3	24	m	r	RG NFT HF	RG FT HF	75
9	26	f	r	RG NFT HF	RG FT HF	68
22	23	m	r	RG NFT HF	RG FT HF	80
7	21	f	r	RG FT IF	RG NFT IF	72
8	27	m	a	RG FT IF	RG NFT IF	79
14	23	f	r	RG FT IF	RG NFT IF	69
21	26	m	a	RG FT IF	RG NFT IF	83
12	23	f	r	RG NFT IF	RG FT IF	71
15	27	m	a	RG NFT IF	RG FT IF	80
19	22	f	r	RG NFT IF	RG FT IF	68

FT= Fixed Targets, NFT= Non-fixed targets

HF=Hand Feedback, IF=Indirect Feedback

Appendix B- Conversion from Pixels to Degrees

In order to convert error in pixels to error in degrees, a conversion value was calculated. It was known that all lines were drawn separated by 10 degrees of visual angle, and therefore the number of pixels per one degree of visual angle was equal to the distance between two lines (in pixels) divided by 10. When this calculation was done for all non-excluded participants, the result indicated an average of 13.8 pixels per one degree of visual angle. This meant all errors reported in pixels in the results could be converted to error in visual degrees by dividing by 13.8. Thus, an error of “50” in pixels, was equivalent to 50 / 13.8 = “3.6” error in degrees of visual angle.

Comparing Pixels to Degrees

Since participants were positioned at different distances from the display (based on arm length) the number of pixels per degree of visual angle also varied by participant. Thus, there was concern that a change from pixels to degrees may systematically change the overall pattern of results (as conversion values were different for different participants - see Table Appendix-B1). Fortunately, a re-analysis of the data with the new error value (degrees of visual angle as modified based on each participants’ conversion value) indicated no changes in the pattern of results. Thus, converting error to error in degrees did not change the overall results or interpretation of data reported in this study. Therefore, all figures included an axis with values in degrees of visual angle based on the *average* group conversion value of 13.8.

Table Appendix-B1.

```
#   id     PixPerDeg   dist.(cm)
#1   1        15.0     79.0
#2  10        12.9     68.0
#3  11        13.2     70.0
#4  13        13.6     72.0
#5  14        13.4     71.0
#6  15        14.2     75.0
#7  16        13.1     69.0
#8  18        15.1     80.0
#9  19        14.7     77.5
#10  2        12.5     65.0
#11 20        12.7     67.0
#12 22        14.4     76.0
#13 23        12.9     68.0
#14 24        12.9     68.0
#15 25        15.7     83.0
#16 26        15.1     80.0
#17 27        13.6     72.0
#18 28        13.6     72.0
#19  3        14.2     75.0
#20  4        13.1     69.0
#21  5        13.8     73.0
#22  6        12.7     67.0
#23  7        13.6     72.0
#24  9        15.0     79.0
Average:      13.8     72.8
```

Variance in Arm Length

As a final check, an analysis of arm length / distance from the display was done. This analysis was done to ensure there was no systematic variance in arm length based on the between-groups conditions. An ANOVA was used, with arm length as the DV and the the between-subjects variables: goggles and feedback type as predictors. No significant differences were found, which, indicated no bias in arm length across experimental conditions. However, there was a small trend towards shorter arms in the left-shifting goggles condition (see ANOVA table from R output, below).

```
ANOVA results
                      Df Sum Sq Mean Sq F value  Pr(>F)
goggles                1  29911 29910.8  3.6283 0.07129 .
feedback_type          1   2438  2437.9  0.2957 0.59258
goggles:feedback_type  1   3284  3284.5  0.3984 0.53505
Residuals             20 164875  8243.7

    goggles   feedback_type       mean
1   Left      Hand Feedback       72.10006
2   Left      Ind. Feedback       69.66667
3   Right     Hand Feedback       74.49745
4   Right     Ind. Feedback       74.57143
```

Overall, we felt these analyses supported the conclusion that the results were the same whether reported in pixels or degrees of visual angle.