UNIVERSITY OF PAVIA – IUSS SCHOOL FOR ADVANCED STUDIES PAVIA

Department of Brain and Behavioral Sciences (DBBS)
MSc in Psychology, Neuroscience and Human Sciences

The Role of Prismatic Adaptation and Sex Differences in the Modulation of Attention in Young Adults

Supervisor:
Prof.ssa Martina Gandola

Co-Supervisor:
Dott.ssa Laura Facci

Thesis written by:
Ghazaleh Ghalichi

Academic year 2025/2026

Abstract

Prismatic Adaptation (PA) is a sensorimotor rehabilitation technique for modulating the dorsal attentional network in patients with visuospatial deficits. However, its capacity to enhance higher-order attentional processing in healthy systems, alongside the potential moderating role of biological sex, remains unclear. This study aimed to determine whether PA can improve the efficiency of higher-level attentional networks (Alerting, Orienting, and Executive Control) in healthy young adults, and to explore whether these cognitive aftereffects differ between men and women. Forty healthy young adults (20 females, 20 males) were randomly assigned to either an experimental PA group, exposed to a 10° rightward optical shift, or a Sham Control group. Participants completed the Attention Network Test (ANT) before and after a pointing procedure to evaluate changes in attentional efficiency. The Real PA group successfully achieved sensorimotor adaptation, demonstrating a significant initial pointing error followed by robust spatial aftereffects that persisted through the delay. However, ANT results showed no significant improvement in higher-level attentional networks. Decreased reaction times accompanied by increased error rates in both groups suggested a generalized speed-accuracy trade-off or task fatigue. Furthermore, while females exhibited significantly higher overall alerting efficiency, and males demonstrated improved conflict resolution over time, these sex-specific variations occurred independently of the PA manipulation. Overall, the findings suggest a functional boundary in healthy individuals, indicating that cerebellar-mediated sensorimotor alignment does not readily transfer to higher-level attentional networks. Additionally, the observed attentional variations highlight the influence of sex-specific cognitive strategies rather than a sex-dependent response to sensorimotor plasticity.

Keywords: Prismatic Adaptation, Attentional Networks, Sex Differences, Attention Network Test (ANT)

Chapter 1. Introduction

1.1 Attention

1.1.1 Theoretical background and Foundations of Attentional Networks

James characterized attention as the process by which the mind clearly and vividly takes possession of a single object or train of thought, selecting it from a multitude of simultaneous possibilities (James, 1890). Attention is not a unitary process but a set of independent systems, which can interact in certain conditions to ensure maximum behavioral efficiency (Forte et al., 2024). Recent theories have conceptualized attention as comprising three separate functional components: alerting, orienting, and executive control systems (Fan & Posner, 2004). First, the alerting system, governed by the right hemisphere, allows for enhanced activation and increased responsiveness to stimuli (Forte et al., 2024). It is linked to arousal system and sustained attention that favor faster responses to stimuli (Forte et al., 2024). The alerting network regulates the level of arousal and activation for both momentary readiness to imminent events (phasic alertness) and sustained performance over long time periods (tonic alertness or vigilance) (Coll-Martín et al., 2021). The attentional component of alerting subsumes the capacity to increase vigilance to an impending stimulus (Fan & Posner, 2004). Alertness can be tonic, defined as the cognitive control of wakefulness and arousal; or phasic, which represents the ability to increase response readiness to the target after an external warning stimulus in reaction time tasks (Mannarelli et al., 2015).

The second subsystem is the orienting network, responsible for prioritizing sensory inputs by selecting a modality or spatial location or object (Coll-Martín et al., 2021). The orienting function involves the component of attention that supports the selection of specific information among numerous sensory inputs (Fan et al., 2009). Orienting can be reflexive or more voluntary. Orienting that does not involve head and/or eye movement is referred to as covert orienting (Fan & Posner, 2004).

Executive control of attention involves more complex mental operations engaged during monitoring and resolving conflict between computations (Fan et al., 2009). Executive control is most needed in situations that involve planning or decision-making, error detection, novel or not well-learned responses, conditions judged difficult or dangerous, and in overcoming habitual actions (Fan & Posner, 2004). This network has been related to the control of goal directed

behavior, target detection, error detection, conflict resolution and inhibition of automatic responses (Berger & Posner, 2000a). The executive control network appears to encompass midline frontal regions, specifically incorporating the anterior cingulate gyrus, the supplementary motor area (SMA), and sections of the basal ganglia (Berger & Posner, 2000b). Functional brain imaging has demonstrated that these regions become active during cognitively demanding operations, including managing conflict, processing novel information, forming expectations, and identifying errors. (Posner & DiGirolamo, 1998).

1.1.2 Attentional Networks (Anatomy and Circuitry)

Attention can be treated as an organ system with its own anatomy, circuitry, and set of functions (Fan & Posner, 2004). Alerting, orienting, and executive control are widely thought to be relatively independent aspects of attention that are linked to separable brain regions (Fan et al., 2005). There is widespread agreement from imaging and cellular recording studies that orienting to sensory information activates a common network of neural areas even before a target is presented (Fan et al., 2005). This suggests that there is a specific network that serves as the source of the enhancement of neural signals related to processing a target (Fan et al., 2005).

Similarly, neuroimaging studies have revealed a specific network of areas that relate to obtaining the alert state and to resolving conflict among responses (Fan et al., 2002). Although previous imaging studies suggest that the networks of neural areas serving as the sources of the orienting, alerting, and conflict effects are anatomically separable, there is substantial functional overlap (Fan et al., 2005). These attentional functions are mediated by anatomically distinct neural networks (Xiao et al., 2016).

Alerting: The neuroanatomy of alerting includes a network of subcortical and cortical regions (Sturm & Willmes, 2001). Alerting would activate the frontal and parietal areas of the right and/or left hemisphere and thalamic areas that are potentially related to norepinephrine (Fan et al., 2005). The nuclei of the reticular formation in the brain stem, specifically the locus coeruleus-norepinephrine (LC-NE) system, is the core arousal center (Everitt et al., 1995). The LC projects to the thalamic nuclei and terminates in cerebral cortex (Foote et al., 1983). In general, the LC-NE system supports appropriate levels of alertness to maintain efficient information processing (Ross

& Van Bockstaele, 2021). Norepinephrine, the neuromodulator associated with the alerting network, appears to inhibit spontaneous neural activity, permitting increased neural response to sensory stimulation (Foote et al., 1975). The anterior cingulate cortex (ACC) and the right dorsolateral prefrontal frontal cortex (DLPFC) function to maintain endogenous alertness by modulating activity in the LC via the reticular nucleus of the thalamus (Sturm et al., 1999). Early neuroimaging and lesion studies together with evidence of a right hemisphere bias in NE have suggested a right hemisphere basis for sustained attention (Fan et al., 2005). Lastly, the alerting network is mediated by a right-lateralized ventral frontoparietal network, which is responsible for achieving and maintaining appropriate levels of alertness (Corbetta et al., 2008). However, more recent fMRI studies have proposed that cues calling attention to a temporal interval might activate left hemisphere areas (Coull & Nobre, 1998).

Orienting: There is widespread agreement on the brain areas involved in orienting toward the spatial location of multiple sensory modalities (Spence et al., 1998). The network of areas responsible for directing attention include superior parietal lobe, intraparietal sulcus, temporal-parietal junction, dorsofrontal cortices (particularly the Frontal Eye Fields; FEF), thalamus, and superior colliculus (Corbetta & Shulman, 2002; Mesulam, 1990). Orienting would activate a superior parietal region and the temporal parietal junction, with a right hemisphere bias. Furthermore, the cerebellum may also play a role in both covert and overt orienting of attention (Akshoomoff et al., 1997; Pélisson et al., 2003). Evidence from individuals with cortical and subcortical lesions suggests that reflexive orienting is likely mediated by subcortical and more posterior cortical regions, while a network of frontal-parietal regions underlie voluntary orienting (Friedrich et al., 1998). Reflexive, or exogenous, orienting is initiated by external sensory signals and involves an automatic shift of attention toward a salient peripheral stimulus (Friedrich et al., 1998). Cholinergic systems arising in the basal forebrain may play an important role in modulating orienting (Cykowski & Masdeu, 2025). Acetylcholine (ACh) is the neuromodulator associated with the orienting network, with increased levels of ACh resulting in more rapid attention reorienting (Pulopulos et al., 2019; Witte et al., 1997). Specifically, ACh may act to expand the attentional spotlight so that attentional misdirection does not elicit a reorienting response (Thiel et al., 2005). In line with this interpretation, Thiel et al. (2005) showed that cholinergic stimulation via nicotine reduced reorienting costs and modulated activity in parietal attention networks, particularly during invalid cue conditions (Thiel et al., 2005). This suggests that acetylcholine

enhances the spatial stability of attention, reducing the need for rapid attentional shifts (Vossel et al., 2014).

Executive Control: The neural substrates of executive control include regions within the prefrontal cortex, orbitofrontal, ventrolateral prefrontal, and dorsolateral prefrontal cortex (DLPFC), as well as medial frontal regions (anterior cingulate cortex; ACC) and subcortical regions such as the basal ganglia and cerebellum (Heyder et al., 2004). Additionally, more posterior areas (mainly located in the parietal lobe) may also be important for executive processes (Collette et al., 2006; Sylvester et al., 2003; Wager et al., 2004a). Accumulating evidence shows involvement of the basal ganglia, more specifically the caudate nucleus, in cognitive functioning (Grahn et al., 2008). The basal ganglia have been particularly critical in mediating the connection between executive attention and other attentional operations (Fan et al., 2005). A few neuroimaging studies have shown that dorsal ACC is involved in dealing with conflict resolution when a person is required to respond based on one stimulus dimension while ignoring another conflicting dimension (Fan et al., 2005). Lateral areas of the frontal cortex have also often been identified with executive attention (Berger & Posner, 2000b). While earlier literature suggested these frontal regions might be organized strictly by the type of information processed (e.g., distinguishing between spatial, verbal, or object features) (Nee & D'Esposito, 2016), more recent meta-analyses indicate a functional organization based on executive operations (Berger & Posner, 2000b). Specifically, distinct frontal regions appear to mediate specific cognitive control processes regardless of the stimulus modality. For instance, the right inferior frontal cortex is strongly associated with inhibitory control (Aron et al., 2004). In terms of working memory, the organization appears to be process-specific: bilateral dorsal frontal regions (such as the superior frontal sulci) are integral for updating information, whereas right ventral frontal regions are recruited for manipulating that information (Wager et al., 2004b). Finally, the ability to shift between tasks or mental sets is likely mediated by a network including the bilateral medial frontal cortex (ACC), intraparietal sulci, and to a lesser extent, the anterior insula and DLPFC (Wager et al., 2004b). Crucially, the efficacy of these executive networks relies on specific neuromodulator inputs. The anterior cingulate and lateral frontal cortices are dense target areas of the ventral tegmental dopamine system (Elston & Bilkey, 2017). While dopamine is traditionally considered the primary neuromodulator supporting the stability of representations in the prefrontal cortex and working memory, it does not act in isolation (Surmeier, 2007). Norepinephrine also plays a vital, complementary role. Beyond its involvement in general

arousal, norepinephrine is specifically implicated in fine-tuning the inhibitory control and set-shifting capabilities mediated by the frontal networks discussed previously (Robbins, 2000).

1.1.3 The Attention Network Test (ANT)

To assess simultaneously the three attentional systems suggested by Posner and Petersen's model, several authors have employed the Attention Network Test (ANT) (Fan et al., 2002). This task was developed to measure the efficiency of the alerting, orienting, and executive control networks in a single procedure by combining a cued reaction-time paradigm with the flanker task (Fan et al., 2002; Zani & Proverbio, 2017; Eriksen & Eriksen, 1974). In this task, participants fixate on a central cross while a target appears, consisting of a central arrow flanked by distractor arrows pointing in either the same (congruent) or opposite (incongruent) direction (Fan et al., 2005). Participants must press a left key for a left-pointing central arrow and a right key for a right-pointing central arrow. To measure the alerting and orienting networks, four cue conditions are introduced before the target appears above or below the fixation point: the no-cue condition (baseline); the center cue, which appears on the fixation point to involve alerting only; the double-cue condition, which uses two cues at the two possible target locations to involve alerting without orienting; and the spatial cue, which appears at the target location to involve both alerting and orienting (Fan et al., 2005).

Rather than providing a single metric of attention, the ANT yields mean reaction times (RT) and accuracy rates across these different conditions, allowing for the calculation of three specific network efficiency scores using subtractive methodology (Fan et al., 2002; Hu et al., 2012). The efficiency of the alerting network is calculated as the difference between the no-cue and double-cue conditions; a larger score typically indicates a greater reliance on warning signals to maintain readiness, a pattern often observed in populations with difficulty maintaining intrinsic alertness (Fan et al., 2002, 2009). The orienting network efficiency is derived by subtracting the mean RT of the spatial-cue condition from the center-cue condition. A larger orienting score generally reflects a higher "cost" of disengaging attention from a central fixation, similar to deficits observed in patients with parietal damage (Posner et al., 1984). This may also indicate that a subject is utilizing the spatial cue more effectively to speed up processing (Posner et al., 1988). Finally, the

executive control (conflict) score is computed as the difference between incongruent and congruent trials, where a higher score mostly indicates greater difficulty in resolving conflict (Fan et al., 2002).

To interpret these scores correctly, one must consider both the calculated network effects and the participant's overall response strategy. Because a "conservative" response strategy, prioritizing accuracy over speed, will naturally inflate the RT conflict score, researchers must perform an analysis of error rates to rule out strategic differences; for instance, if one group shows a larger RT conflict effect with high accuracy while another shows a smaller RT effect with high error rates, the difference likely reflects a shift in strategy rather than capacity (Davidson et al., 2006; Salthouse, 2010). Ultimately, the ANT has been remarkably successful in simultaneously studying the efficiencies and interactions of these three independent networks and their connection to the specific brain areas involved in the control of attentional functions (Posner & Rothbart, 2007).

1.2 Prismatic Adaptation

1.2.1 Theoretical Background and Neural Mechanisms

Prism adaptation (PA) is a non-invasive and widely investigated rehabilitation technique, primarily employed to ameliorate Unilateral Spatial Neglect (USN), a debilitating neurological condition frequently resulting from right-hemisphere stroke (NAITO et al., 2025). Patients with USN exhibit a systematic failure to attend to or represent the contralesionally (left) side of space, affecting both visual perception and mental imagery (Bisiach & Luzzatti, 1978; KM, 1985). Historically, the foundational principles of PA date back to early perceptual experiments by Stratton (1896) and Helmholtz (1925), who explored the plasticity of the visual system (Helmholtz & Southall, 1925; Stratton, 1896). By the mid-20th century, researchers such as Harris (1963) and Held and Freedman (1963) formalized the understanding of sensorimotor adaptation, demonstrating that the brain can rapidly recalibrate motor output in response to altered visual input (Harris, 1963; Held & Freedman, 1963). In its contemporary clinical application, established by the seminal work of Rossetti et al. (1993), the procedure requires the participant to perform a visuomotor pointing task while wearing prismatic goggles that displace the visual field laterally (typically shifting the visual

field 10–15 degrees to the right) (Rossetti et al., 1993a). The adaptation process unfolds in three distinct stages: First, an initial pointing error in the direction of the optical shift (direct effect). The magnitude of the direct effect experienced at the onset of prism exposure cannot be perfectly predicted by the degree of optical displacement alone (Redding & Wallace, 2003). While the sensorimotor error consistently follows the direction of the prism shift and is roughly proportional to it, the actual deviation often falls significantly short of the full optical value (Redding & Wallace, 2003). This discrepancy includes an 'immediate correction effect,' as demonstrated by Rock et al. (1966), who found that in a structured visual environment, perceived displacement may be reduced to as little as 40% of the actual prism strength, even when the participant cannot see their own body (Rock et al., 1966). Furthermore, this effect is modulated by the 'straight-ahead shift' a phenomenon where the participant's cognitive judgment of the subjective midline realigns with the center of the displaced visual field (Harris, 1974). Consequently, objects are judged to be closer to the 'straight ahead' position than they optically appear, effectively dampening the immediate impact of the prismatic displacement (Harris, 1974). Finally, the magnitude of the direct effect is significantly dampened by what is known as 'first trial adaptation' (Redding & Wallace, 2003, 2004). Empirical evidence shows that the pointing error on the very first exposure trial is often far smaller than the optical displacement would predict, even when the hand is visible only at the end of the movement to prevent in-flight correction (Redding et al., 2005a). For instance, a 10-degree optical shift may result in a pointing error of only 4 degrees—mere 40% of the expected deviation (Redding et al., 2005a). These findings indicate that the immediate direct effect of prismatic displacement is not a simple optical translation but a complex interaction of sensory weighting and rapid neural recalibration (Redding et al., 2005a). Furthermore, the temporal dynamics of error reduction during prism exposure exhibit significant complexity. Generally, the pointing error at the movement's end (terminal error) diminishes rapidly, often returning to baseline accuracy levels within approximately 15 trials, as the participant learns to direct movement toward the actual rather than the virtual target location (Redding & Wallace, 1993; Rossetti et al., 1993b). However, the rate of this error reduction is highly dependent on the nature of visual feedback available during the pointing motion (Redding & Wallace, 1993; Uhlarik & Canon, 1971). When the limb is visible during the latter part of the trajectory ('concurrent exposure'), error correction occurs in fewer trials compared to conditions where only the fingertip is visible upon completion ('terminal exposure'), provided the movement speed allows for online

correction (Rossetti et al., 1993b). Furthermore, if the adaptation task continues after accuracy is achieved (i.e., zero terminal error), a phenomenon of 'overcompensation' may emerge, where the errors begin to occur in the direction opposite to the prismatic shift (Redding et al., 2005a). This overcompensation is particularly prevalent under conditions of terminal exposure (Redding & Wallace, 1990, 1992, 1993, 1994). If the full movement path from starting to target positions is visible, no direct effect of the prismatic displacement is observed (Redding & Wallace, 1996, 1997). Similarly, if concurrent exposure and very slow movements toward the target is used, direct effects may not appear (Redding et al., 2005a). Third the emergence of a negative aftereffect upon removal of the goggles (Redding et al., 2005b). This aftereffect, an involuntary leftward deviation of pointing in the absence of prisms, confirms that a realignment of the sensorimotor coordinates has occurred (Redding et al., 2005a). The therapeutic rationale for using PA in neglect lies in the mechanism in which the sensorimotor realignment induces a "bottom-up" reset of the dorsal attentional network, effectively shifting the patient's egocentric reference frame toward the neglected left side and alleviating symptoms across various cognitive domains (Frassinetti et al., 2002; Pisella et al., 2006). The aftereffects of prism adaptation represent perhaps the most intricate component of the process. The magnitude of the aftereffect is often context-dependent, showing greater strength when the testing conditions closely mirror the training conditions, such as in movement speed (Kitazawa et al., 1997) or limb posture (Martin et al., 1996). This specificity is so robust that 'dual adaptation' is possible: participants can simultaneously adapt to two different prism displacements if the exposure conditions are distinct enough to elicit separate aftereffects during testing (Bingham & Romack, 1999; Martin et al., 1996; Redding & Wallace, 2003). Conversely, under certain parameters, aftereffects can demonstrate complete generalization, transferring uniformly across all coordinates within the spatial reference frame used during exposure (Bedford, 1993; Guigon & Baraduc, 2002; Redding & Wallace, 1997). Local aftereffects can manifest within distinct sensorimotor systems and their associated reference frames, such as the visual (eye–head) or proprioceptive (hand–head) systems (Redding et al., 2005a). Research indicates that these local changes are additive; they summate to produce the total adaptation observed in the inclusive coordination loop (e.g., eye–hand) used during exposure (Redding & Wallace, 1993; Templeton et al., 1974).

Crucially, the relationship between the initial direct effects (errors) and the subsequent aftereffects is not straightforward (Redding et al., 2005b). Most immediate responses to prisms do not translate into lasting adaptation (Redding et al., 2005b). Studies show that the 'immediate correction effect' (Wallace et al., 1973), 'visual capture' (Welch, 2013), and 'first-trial adaptation' (Redding & Wallace, 2004) generally fail to produce reliable aftereffects. Of the various initial responses to prism exposure, only the 'straight-ahead shift' appears to be associated with the development of persistent aftereffects under specific conditions (Redding, 1978). The correlation between the reduction of terminal error during exposure and the subsequent aftereffects is non-linear and complex (Redding et al., 2005b). While participants typically achieve 100% compensation for the optical displacement during the exposure phase, the resulting aftereffects generally account for only about 40% of the shift (Redding & Wallace, 1993). Research indicates that the phenomenon of 'overcompensation' during exposure is positively correlated with the magnitude of these aftereffects (Redding & Wallace, 1990, 1994). Crucially, the nature of visual feedback dictates whether adaptation occurs at all: if the entire movement path is visible, neither direct effects nor aftereffects typically develop (Redding, 2001; Redding & Wallace, 1996); While restricting visibility to the starting and target positions facilitates both effects, adaptation interestingly does not require the conscious detection of error (Redding et al., 2005a). Aftereffects successfully emerge even when the prismatic displacement is introduced so gradually that no performance error is detectable (Dewar, 1971; Jakobson & Goodale, 1989). In fact, evidence suggests that aftereffects are often larger when the participant remains unaware of the visual displacement (Michel et al., 2003), demonstrating that aftereffects and direct effects are distinct phenomena that can occur independently of one another (Weiner et al., 1983).

1.2.2 Adaptive processes

Prism exposure triggers a sophisticated array of mechanisms that influence how we perceive and move, both while wearing the prisms (direct effects) and after they are removed (aftereffects) (Redding & Wallace, 1997). These processes are categorized into three distinct classes: Postural Adjustments, Strategic Control, Spatial Realignment. First, postural adjustments arise from the sensory-motor asymmetry created by the optical shift and manifest through two primary

mechanisms: inter-sensory bias and muscle potentiation (Redding et al., 2005b). Inter-sensory bias, most notably "visual capture," occurs when the brain prioritizes visual input over proprioception, causing a person to feel their limb or head is located where it appears to be rather than where it physically exists (Hay et al., 1965; Redding & Wallace, 2003). While these biases help reduce errors during prism exposure by effectively "canceling out" the optical displacement, they do not produce lasting aftereffects (Welch & Warren, 1980). Conversely, muscle potentiation comes from the physical strain of holding an asymmetric posture, like keeping eyes or a limb pointed in one direction. This strain can actually shift what those muscles consider "straight ahead," leading to noticeable aftereffects (Ebenholtz, 1974; Redding, 1978). However, research indicates that muscle potentiation is not the sole driver of adaptation, as aftereffects can still emerge in the absence of such physical strain (Craske & Crawshaw, 1975). Second, strategic control involves the conscious or pre-conscious management of movement plans aimed at achieving specific performance goals (Redding & Wallace, 1997). Central to this process is recalibration, a form of associative learning in which the brain utilizes "knowledge of results" from previous failed attempts to adjust subsequent movements; for instance, if a participant misses a target to the left, strategic control dictates aiming further to the right in future trials (Welch & Warren, 1980). While these strategic corrections can lead to aftereffects, they exhibit high context specificity, often remaining limited to conditions that closely mirror the original training environment (Redding & Wallace, 2002). However, strategic control cannot be the sole mechanism of adaptation, as research has demonstrated that aftereffects can successfully emerge even in the absence of consciously detectable performance errors (Dewar, 1971; Jakobson & Goodale, 1989). Third, spatial realignment, considered the "core" of prism adaptation and the primary source of global aftereffects, occurs when the brain detects a spatial discordance between the expected outcome of a feedforward movement plan and the actual sensory feedback received (Redding & Wallace, 1993, 1997). This detection is essential; if movements are performed slowly enough to be entirely governed by online visual feedback, no error signal is generated, and "true" realignment fails to take place (Redding & Wallace, 1996). As a form of non-associative learning, spatial realignment is distinct because it generalizes across the entire reference frame, impacting any task associated with that specific spatial map (Bedford, 1993). Interestingly, strategic recalibration can actually hinder this process; if a conscious strategy is highly effective at reducing

performance errors, the brain perceives less of a mismatch, thereby reducing the drive to fundamentally realign its internal spatial representations (Redding & Wallace, 1993).

1.2.3 Calibration versus alignment

Building on the framework established by Redding and Wallace (1997a, 2002), a critical distinction must be drawn between calibration and alignment as different mechanisms in the prismatic adaptation process. Calibration is a high-level, strategic function responsible for defining a specific 'task-workspace' within the broader perceptual environment (Redding & Wallace, 2003). It functions to optimize precision and efficiency by actively mapping egocentric (self-centered) reference frames onto allocentric (externally-centered) ones (Redding & Wallace, 2002). This process is intentional and attention-driven, relying on strategic control to identify targets and recruit the necessary effectors for a specific plan (Redding et al., 2005b). In contrast, alignment serves as the foundational prerequisite for calibration (Redding et al., 2005b). It involves the automatic computation of the constant parameters that define the relationship between the origins and axes of different sensorimotor coordinate systems (e.g., the fixed physiological distance between the eyes and the shoulder) (Redding et al., 2005b). A defining characteristic of this hierarchy is 'transparency': the state of alignment is hidden from the calibration process (Redding et al., 2005b). Because strategic control presupposes that coordinate systems are correctly aligned, it does not 'see' misalignment directly (Redding et al., 2005b). Consequently, when fundamental alignment errors occur (as induced by prisms), the high-level calibration system misinterprets them as simple execution errors, unaware that the underlying coordinate constants have changed (Redding & Wallace, 2002). Empirical and Neuroanatomical Evidence for the Two-Process Model Direct empirical support for the distinction between strategic calibration and spatial alignment is found in the dissociation of error patterns and adaptation rates (Redding et al., 2005b). Redding and Wallace (2001) demonstrated that while visual calibration improves precision (reducing variable error), it paradoxically increases constant error under prismatic misalignment compared to proprioceptive conditions (Redding, 2001). Furthermore, the temporal dynamics of these processes differ significantly: strategic recalibration rapidly eliminates performance errors (direct effects) during early exposure, whereas spatial realignment develops slowly and often fails to reach

complete compensation (Redding et al., 2005b). This asynchrony explains the phenomenon of "overcompensation" observed in later trials, where the additive effect of rapid strategic correction and the emerging transparent realignment results in a "double correction" error (Redding & Wallace, 1993). Crucially, this behavioral distinction is mirrored by a neuroanatomical double dissociation between the cerebrum and the cerebellum (Redding et al., 2005b). Research indicates that strategic calibration relies on the posterior parietal cortex (PPC), while spatial alignment is mediated by the cerebellum (Jeannerod & Rossetti, 1993). Clinical studies involving lesion patients provide definitive proof of this separation: patients with cerebellar damage can reduce performance errors during exposure using intact parietal strategies but fail to generate aftereffects, indicating a specific failure of realignment (Martin et al., 1996; Weiner et al., 1983). Conversely, patients with damage to the PPC exhibit the reverse pattern; they retain the ability to generate aftereffects (intact cerebellar realignment) but show significantly slowed error correction during exposure due to the loss of strategic recalibration mechanisms (Pisella et al., 2004).

1.3 Sex Differences in Attention

For decades, the existence of sex-based cognitive disparities has been a subject of significant academic debate and interest (Gang et al., 2013). Research indicates distinct advantages for each sex: females typically demonstrate superior efficiency in selective attention, verbal fluency, and reasoning tasks (V. Anderson, 2001; V. A. Anderson et al., 2001; Klenberg et al., 2001; Schaie, 1994), whereas males generally excel in visuospatial processing, particularly mental rotation (Astur et al., 1998; Collins & Kimura, 1997; Dabbs Jr et al., 1998; De Luca et al., 2003; Weiss et al., 2003). These functional differences are likely rooted in neuroanatomical development (Gur et al., 1999). Specifically, while females experience earlier maturation peaks in frontal and parietal regions, males exhibit steeper developmental trajectories regarding gray matter reduction and white matter volume increases (De Bellis et al., 2001; Giedd et al., 1999). Maciejewska and her coworker provided evidence that men and women may have distinct neuronal activation patterns during cognitive tasks involving attention (Maciejewska & Froelich, 2021). Studies show that women showed increased suppression of the Default Mode Network (DMN) and the Dorsal Attention Network (DAN) compared to men during exposure to reward and punishment (Dumais

et al., 2018a). The DMN is typically associated with internal self-referential thought (mind-wandering) (Pu et al., 2016) and the DAN is associated with externally directed attention (Dumais et al., 2018b).

Findings regarding the orienting network have been mixed. Early research by Urbanek et al. (2009) reported no significant sex differences, but later studies identified a clear female advantage (Gang et al., 2013; Urbanek et al., 2010). Specifically, females demonstrated a much larger orienting effect, meaning they are more efficient at covertly directing their attention to spatial cues. According to Rubia et al. (2010), this heightened ability essentially allows females to use spatial cues more effectively than males (Rubia et al., 2010). Furthermore, research indicates that sex-based differences in attention are specific to the type of orienting required. Studies consistently show that females exhibit larger validity effects when targets are preceded by endogenous (voluntary) cues, but not exogenous (reflexive) ones (Bayliss et al., 2005; Feng et al., 2011; Merritt et al., 2007). To clarify these findings, it is useful to define the validity effect (calculated as the difference in response time between invalid and valid trials) as a measure of the cost of orienting to an incorrect location relative to the benefit of orienting to a correct one (Jonides, 1980). By comparing these trials to a no-cue control condition, researchers can isolate the specific benefits of selective attention, the speed gained by valid cues, from the costs incurred when attention is misdirected by invalid ones. The divergence in sex-based performance is rooted in the fact that endogenous and exogenous attention are distinct functional processes, despite engaging overlapping neural networks (Corbetta and Shulman, 2002; Corbetta et al., 2008; Chica et al., 2013; Buschman and Kastner, 2015). As Wright and Ward (2008) detail, several key differences distinguish these systems: endogenous attention is goal-directed and slow to engage, whereas exogenous attention is stimulus-driven and shifts rapidly. Exogenous attention also uniquely features "inhibition of return"—a delay in re-engaging with a previously attended stimulus—to promote exploratory behavior (Klein, 2000). Conversely, endogenous attention is highly sensitive to top-down executive resources; for example, Jonides (1981) demonstrated that manipulating cognitive load selectively impairs endogenous performance while leaving exogenous orienting largely intact. Given these distinct behavioral signatures and their varying susceptibility to interference, the prevailing view in the field is that visuospatial attention is governed by functionally separable systems.

Regarding the alerting network, research into sex-based differences has yielded mixed results. Liu et al. (2013) and Urbanek et al. (2009) reported no significant differences between males and females (Liu et al., 2013; Urbanek et al., 2010). This lack of consensus extends to studies using the Attention Network Test (ANT), where findings remain scarce and contradictory; for instance, while Miró et al. (2015) reported a superior alerting network in women, other studies have found no such disparity (Liu et al., 2013). Furthermore, Merchan et al. (2012) observed that men displayed a less efficient alerting network compared with women, while Bayliss et al. (2005) found that males exhibited faster response times than females in endogenous cueing tests. Merritt et al. (2007) added that while both sexes benefited from valid endogenous cues, males also showed a benefit from invalid endogenous cues compared to non-cued controls. Findings regarding broader sustained attention are similarly complex. While some research indicates no sex effect (Chan, 2001), other studies suggest that men exhibit superior vigilance (Blatter et al., 2006), whereas women demonstrate enhanced inhibitory control (Yuan et al., 2008). This distinction is supported by Riley et al. (2016), who observed that men typically display faster reaction times with lower variability, albeit at the cost of higher commission errors (impulsivity). Conversely, women in the same study tended to make more omission errors, failing to respond to targets rather than responding impulsively (Riley et al., 2016).

The literature regarding Executive Control presents the most controversial findings. While some research indicates that females are more susceptible to interference from task-irrelevant information (Evans & Hampson, 2015; Stoet, 2017), Other studies report no significant sex differences in interference control (Shaqiri et al., 2018; Urbanek et al., 2010). Furthermore, another study suggests that women demonstrate enhanced inhibitory control (Yuan et al., 2008). Interestingly, differences may exist at the neural level even when behavioral performance appears identical. For instance, Christakou et al. (2009) found sex-specific neural activation patterns during the Simon task, which assesses the brain's ability to inhibit automatic responses to irrelevant spatial cues, despite no differences in performance outcomes (Christakou et al., 2009). Similarly, Clayson et al. (2011) observed distinct electrophysiological responses to conflict monitoring in the Flanker task, though there is no consensus on which sex monitors conflict more efficiently (Clayson et al., 2011). In terms of response strategy, women generally exhibit higher inhibitory control, characterized by less impulsivity but slower and more variable reaction times (Conners et al., 2003). This appears to be more heavily modulated by the emotional content of stimuli

demonstrating a heightened attentional bias toward valanced stimuli (Bates et al., 2015; Conners et al., 2003; Sarter et al., 2001).

1.4 Specific Focus of the Present Study and Aims

This study investigates the effects of Prismatic Adaptation (PA), a sensorimotor adaptation technique, on attentional sub-components in healthy young adults. Specifically, the influence of sex differences on attentional networks will finally be explored. We utilized the Attention Network Test (ANT) to measure the efficiency of three distinct attentional networks: Alerting, Orienting, and Executive Control. Crucially, this research seeks to determine if the modulation of these attentional networks following PA is moderated by biological sex. We aim to compare the magnitude and direction of cognitive aftereffects between men and women to understand if sensorimotor plasticity differentially impacts cognitive control based on sex.

Research demonstrates that Prism Adaptation (PA) is an effective rehabilitation technique for ameliorating unilateral spatial neglect in stroke patients (Mancuso et al., 2012; Rossetti et al., 1998). This therapeutic efficacy is primarily driven by a sensorimotor realignment that directly modulates the dorsal attentional network. If PA can successfully modulate attention, it is plausible that it also impacts higher-order attentional components defined by Posner's model, specifically Alerting, Orienting, and Executive Control. Therefore, the present study aims to investigate whether the underlying mechanisms of PA can extend beyond clinical rehabilitation to influence and potentially enhance higher-order attentional networks in a healthy population. Furthermore, the existing literature regarding sex-based differences across various attentional networks remains largely inconsistent and inconclusive. Given these ambiguities, we aimed to investigate these potential disparities through our experimental paradigm. By administering the PA intervention and subsequently measuring attentional performance, we seek to determine whether sensorimotor plasticity yields distinctly different cognitive aftereffects in men compared to women, thereby clarifying the role of biological sex in the modulation of attention.

1.5 Hypotheses and Expected Results

We hypothesize that PA can modulate cognitive plasticity and improve higher-level attentional components, leading to significant differences in ANT reaction times between the Real and Sham groups at post-treatment. Consequently, the data analysis is expected to yield a significant improvement in reaction times (RT) and accuracy in the ANT post-adaptation for the total sample, confirming the potential of PA to act as a cognitive enhancer in healthy systems. Crucially, to the best of our knowledge, no previous studies have investigated whether men and women behave differently in response to Prism Adaptation. Because there is currently no literature exploring sex-related differences in the cognitive aftereffects of PA, we cannot firmly predict how each sex will respond to the intervention based solely on general, baseline attentional differences. Therefore, while we anticipate a higher orienting index in women, better executive functionality in men, and a similar result in the alerting index at the pre-adaptation baseline in line with existing literature, our investigation into how biological sex modulates the actual response to PA remains entirely exploratory. This constitutes a major strength and novelty of the present study, as it is the first research to directly investigate this specific aspect. Given this pioneering approach, we do not posit specific directional hypotheses for the Time × Sex × Network interactions. Instead, we aim to openly explore whether the sensorimotor plasticity induced by PA yields distinctly different cognitive aftereffects in men compared to women. These exploratory results will provide the first evidence on whether the cognitive transfer of sensorimotor plasticity is sex-dependent, ultimately suggesting whether future clinical applications of PA should consider patient sex to maximize therapeutic outcomes.

Chapter 2. Methods and Materials

2.1 Participants

40 healthy participants (Age: M = 24.17 ± 3.1; years of education: M = 15.57 ± 2.07; age range: 18-30) have been enrolled from psychology students of the University of Pavia. The sample included 20 women (Age: M = 23.4 ± 3.07; Years of education: M = 15.2 ± 2.17) and 20 men (Age: M = 24.9 ± 3.02, Years of education: M = 15.9 ± 1.96) who were totally naive as to the

purpose of the study. Participants were right-handed (Oldfield's Laterality Quotient M = 0.65). The experimenter verified that all participants met the specific inclusion criteria outlined in the study protocol, excluding any individuals who failed to meet the necessary requirements. The study was limited to individuals with no history of neurological or psychiatric disorders. Participants were also required to have no history of uncorrected primary sensory disorders or progressive sensory impairments, such as vision or tactile deficits. Finally, each participant had to achieve a score within the normal range on the Standard Progressive Matrices (SPM-38) to ensure average cognitive functioning. Ethical approval was obtained from the Ethics Committee of the University of Pavia for the healthy students (Approval Code: 149/23). All subjects gave their informed consent for participation in the study.

2.2 Experimental Procedure

This study utilizes a pre-post experimental design with between-groups comparisons to investigate how prism adaptation influences attentional networks, with participants randomly assigned to either a Real Prism Adaptation group (N=20, Age: M=24.8 ± 3) or a Sham Control group (N=20, M=23.55 ± 3.15). The research protocol is divided into two 40-minute sessions. In the initial baseline session, participants provided informed consent and were assigned unique alphanumeric identification codes to ensure confidentiality while enabling longitudinal data matching. Demographic data, including age, sex, language, education, and profession, were collected alongside a standardized assessment of handedness using the Oldfield (1971) questionnaire (Oldfield, 1971). To establish a baseline for attentional efficiency, participants completed the Attention Network Test (ANT) to measure the Alerting, Orienting, and Executive Control networks, conducted on a standardized 17-inch monitor.

The second session is dedicated to the experimental intervention and the post-test assessment phase. During this time, the researchers implement the prism adaptation procedures for the experimental group or the sham intervention for the control group to observe potential changes in attentional performance and motor behavior. This design ensures that all participants undergo identical environmental and procedural conditions, allowing for a controlled evaluation of the intervention's specific effects

2.2 Materials

2.2.1 Handedness Questionnaire

Participants indicated their preferred hand for ten common activities: writing, drawing, throwing, using scissors, brushing teeth, using a knife (without a fork), using a spoon, gripping a broom (upper hand), lighting a match, and opening a box lid. Each response was assigned 2 points, resulting in a total score out of 20 to determine the degree of right- or left-handedness. Additionally, foot preference (e.g., for kicking a ball) and eye dominance (the eye used for monocular tasks) were recorded (see Figure 2.1).

QUESTIONARIO DOMINANZA MANUALE

(OLDFIELD, 1971)

		L	R
1	Scrivere		
2	Disegnare		
3	Lanciare		
4	Usare le forbici		
5	Usare uno spazzolino per i denti		
6	Usare un coltello (senza forchetta)		
7	Usare un cucchiaio		
8	Usare una scopa (impugnatura superiore)		
9	Accendere un fiammifero		
10	Aprire scatola (coperchio)		
I	Con quale piede preferisce calciare?		
II	Quale occhio usa se ne deve usare uno solo?		

Totale _____/10

Figure 2.1 quantitative assessment of handedness Questionnaire

2.2.2 Standard Progressive Matrices (SPM)

Raven's Standard Progressive Matrices (SPM; (Raven, 2000)) are without doubt one of the most popular and widely used psychometric tests of general ability (Mackintosh, 1998). There are many reasons for this. The Matrices may be administered with ease as either an individual or a group assessment (Langener et al., 2022). The basic version of the test can be used for a wide age range,

consisting of 5 sets of 12 different matrices, gradually increasing in difficulty. Since the test is non-verbal it can be employed in different language communities. We used the Standard Progressive Matrices (SPM) for quantifying General intelligence. The test consists of 60 items of the kind shown in figure 2.2. figures presented in order of increasing difficulty, each containing a missing piece. Participants were instructed to select the correct missing piece from a set of multiple alternatives. In this study, we limited our testing to sets A, B, C, and D (John & Raven, 2003). After calculating the number of correct responses, the final Raven's raw score was converted into a corrected Raven score using the following formula:

Corrected Score = Q2 - ((√F2 - 7.082) × (-0.36)) - ((√G2 - 3.323) × (0.32))

Corrected scores were then transformed into a five-point interval scale, from 0 to 4 equivalent scores (Spinnler, 1987). The cut-off score obtained in the study by Caffarra et al., (2003), was 20.72 and the corresponding equivalent scores for different levels of performance are shown in Table 2.1 (Caffarra et al., 2003).

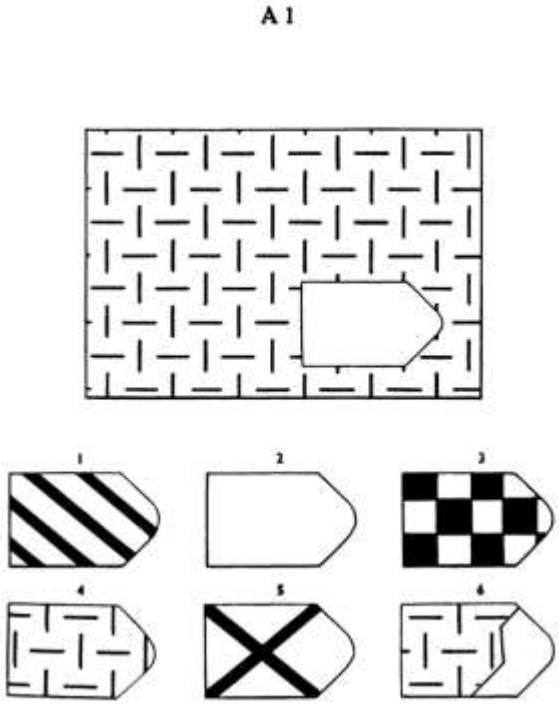

Figure 2.2 Easy Standard Progressive Matrices Test Item

Equivalent score	Total score
0	<20.72
1	20.73–26.26
2	26.27–31.80
3	31.81–37.34
4	>37.35

Table 2.1 Equivalent scores for the total score

2.2.3 Attention Network Test (ANT)

ANT was administered using the Psychology Experiment Building Language (PEBL), an open-source programming system specialized for the creation and execution of computerized cognitive tasks (available at: https://pebl.sourceforge.net). The software was run on a stationary computer equipped with a 17-inch monitor. Participants performed the test individually in a dedicated, sound-attenuated room to minimize external distractions. The experimenter was present to describe the nature of the test and provide instructions. Before the session began, the experimenter ensured participant comfort and confirmed that all mobile devices were silenced. Participants were instructed to sit at a comfortable viewing distance from the screen and to maintain their focus on a central fixation cross throughout the task. The stimuli consisted of black arrows presented against a white background. Participants were required to identify the horizontal direction (left or right) of a central target arrow by pressing the corresponding left or right "Shift" key on the keyboard. The target appeared either above or below the central fixation cross and remained on the screen until a response was recorded. The ANT modulates attention through the manipulation of two primary factors: Congruency and Cueing. The target arrow was flanked by two arrows on either side, resulting in three potential conditions:

Congruent: Flankers point in the same direction as the target (e.g., →→→→→).

Incongruent: Flankers point in the opposite direction (e.g., →→←→→).

Neutral: The target is flanked by horizontal lines with no directional information (e.g., →).

To modulate the alerting and orienting networks, four types of warning cues (asterisks) were presented 100 ms prior to the target onset:

No Cue: No asterisk appears, providing no temporal or spatial information.

Center Cue: An asterisk (*) appears at the fixation cross, providing temporal information (Alerting).

Double Cue: Asterisks appear at both potential target locations (top and bottom), providing temporal information but no specific spatial information.

Spatial Cue: An asterisk appears exactly at the upcoming target location, providing both temporal and spatial information (Orienting).

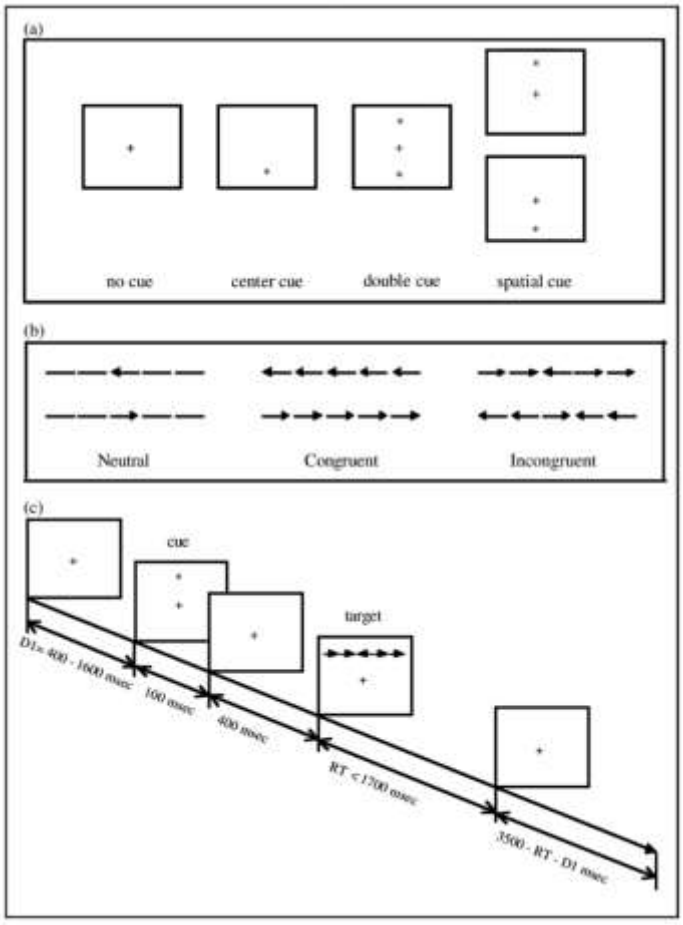

Figure 2.3 (a) The four cue conditions: (b) The six stimuli used in the present experiment: (c) An example of the procedure (Fan et al., 2002).

The full procedure consisted of 312 trials presented randomly across three experimental blocks. The first 24 trials served as a practice session to ensure participants understood the instructions; these data were excluded from the final analysis. The total duration of the task was approximately 22 minutes. Furthermore, Reaction Times (RT) and accuracy were recorded for every trial.

Following the logic established by (Fan et al., 2002), the main outcome measure is the RT difference score, calculated to isolate the efficiency of each network:

Alerting Efficiency: Calculated as the RT for the No Cue condition minus the RT for the Double Cue condition. This reflects the benefit of having a general warning signal.

Orienting Efficiency: Calculated as the RT for the Central Cue condition minus the RT for the Spatial Cue condition. This measures the benefit of knowing the specific spatial location of the target.

Executive Control (Conflict) Efficiency: Calculated as the RT for the Incongruent Flanker condition minus the RT for the Congruent Flanker condition. This represents the cognitive cost of resolving conflicting information.

2.2.4 Prism Adaptation Setup

During the PA procedure, participants were seated at a table in front of a specialized box (Height: 30 cm; Width: 72 cm; Depth: 34 cm at the center, 18 cm at the periphery). The box was open on both the side facing the participant and the side facing the experimenter (Figure 2.4). Three wooden columns, serving as targets, were positioned at the distal edge of the box's top surface. These targets were placed at the objective midline (0) or at lateral locations of 15.5 CM to the left and 15.5 CM to the right of the center. The specific target for each trial was determined according to a randomized sequence. Participants were instructed to start with their right hand positioned at the level of the sternum on their chest. Upon the experimenter's signal, they executed a rapid, ballistic pointing movement toward the designated wooden column using their index finger. A ballistic movement, characterized by a single, fast motion without in-flight adjustments, is necessary to ensure the brain relies on its internal spatial map rather than online visual corrections. After each movement, the participant returned their hand to the starting position at the center of the body. The experimenter recorded the final landing position of each pointing movement to quantify spatial accuracy. For the experimental manipulation, the Real Adaptation group wore goggles fitted with wedge prisms inducing a 10° rightward shift in the visual field. The Control group wore neutral Sham goggles that provided no visual displacement.

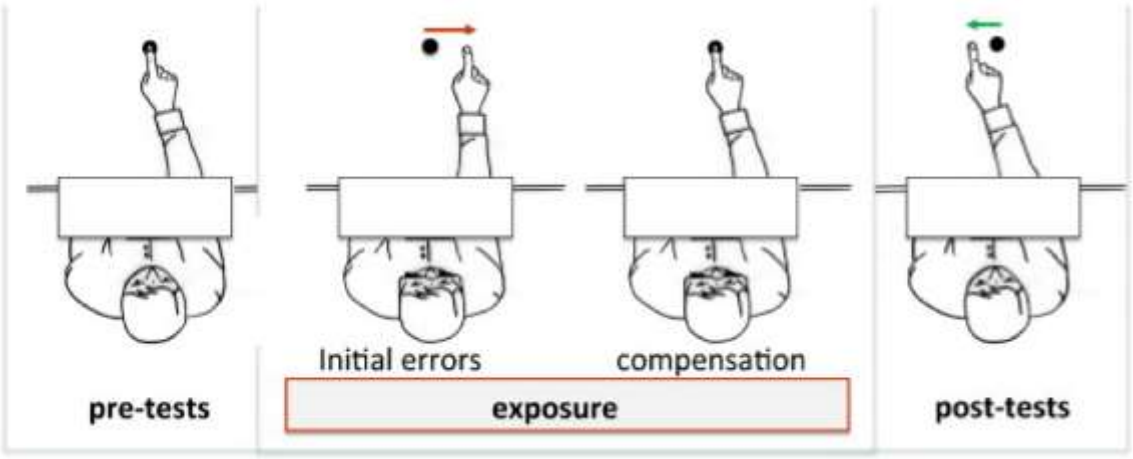

Figure 2.4 Prism Adaptation Procedure

The pointing task was structured into three distinct experimental phases (Figure 2.5):

Pre-exposure (Baseline): Subjects performed a total of 30 trials without prisms to establish baseline accuracy. This consisted of 15 visible pointing trials in which participants could see the final third of their arm's trajectory and the landing position of their finger. This terminal feedback is essential for the error-correction process that drives adaptation. Another 15 invisible pointing trials were performed by participants at this level. A wooden screen obscured the participant's view of their hand and arm throughout the movement.

Exposure (Adaptation): Subjects performed 90 trials while wearing the 10° right-shifting prisms or sham lenses, depending on the experimental Group. These were visible pointing trials, allowing the central nervous system to compensate for the optical deviation.

Post-exposure (Aftereffect): Following the removal of the prisms, participants performed invisible pointing movements underneath the top surface of the box to ensure the index finger was not visible at any stage. This phase comprised 30 trials in total:

Immediate Aftereffect: 15 trials performed immediately after the exposure phase.

Delayed Aftereffect: 15 trials performed after the completion of the second Attention Network Test (ANT) to assess the persistence of the motor recalibration.

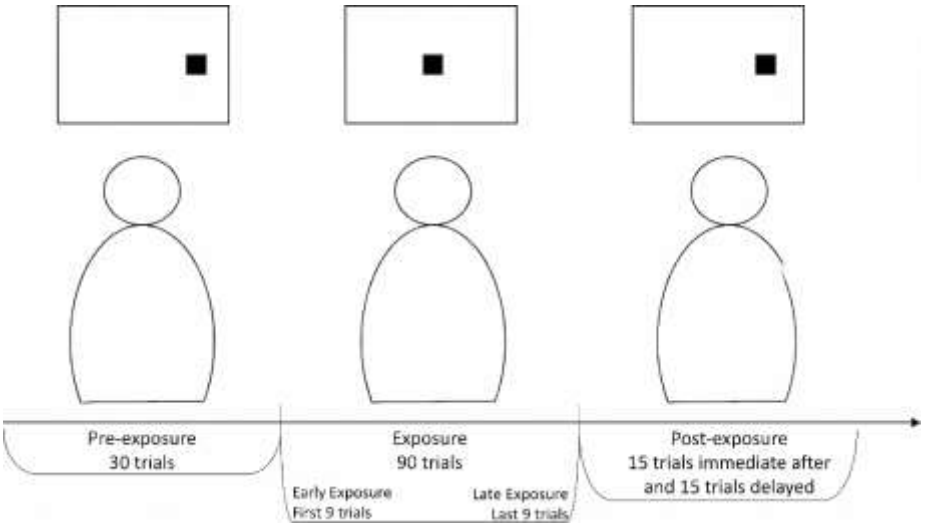

Figure 2.5 Three Distinct Experimental Conditions (Baron et al., 2025).

2.5 Statistical Analysis of Prism Adaptation (PA)

To verify the effectiveness of the sensorimotor intervention and the progression of adaptation, the pointing error data were analyzed using a 2x2 Repeated Measures ANOVA with Group (Real vs. Sham) Between-Subjects variables and Time (Pre vs. Post) as Within-Subject variable. The analysis evaluated the change in pointing performance across Time, specifically comparing the Pre-exposure (baseline) phase to the Early Exposure phase (the initial trials following the introduction of the prisms). This allowed for the quantification of the "prism effect", the initial displacement caused by the optical shift, and the subsequent motor correction. This was used to confirm that the experimental manipulation successfully induced a spatial mismatch in the Real group while maintaining stable performance in the Sham group. By comparing these groups, the analysis ensured that the behavioral changes observed were a direct result of the 10° rightward optical deviation rather than general motor fatigue or repetitive pointing effects.

2.6 Statistical Analysis of ANT

Baseline and Non-Parametric Comparisons: To ensure group equivalence prior to the intervention, Independent Samples T-Tests were performed to compare baseline (Pre-test) ANT scores and Sex

across the experimental groups. In instances where the data violated the assumption of normality, as determined by the previously mentioned Shapiro-Wilk tests, the Mann-Whitney U test was employed as a robust non-parametric alternative. This dual-testing approach ensured that any observed post-intervention changes could be confidently attributed to the prism adaptation effect rather than pre-existing group differences. To evaluate the impact of the PA on attentional performance, a 2x2x2 Repeated Measure ANOVA was performed on the reaction time (RT) data, with Group (Real vs. Sham) and Sex (female vs. male) as between-subjects variables and Time (Pre vs. Post) as within-subject variable. The efficiency of the three attentional networks (Alerting, Orienting, and Executive Control) was first quantified using the subtraction logic established by Fan et al. (2002). A Mixed-Design Repeated Measures ANOVA (RMA) was conducted to examine changes in network efficiency across the experimental sessions. The analysis focused on the interaction between Time (Pre-test vs. Post-test) and Group (Real Prism Adaptation vs. Sham), Time and Sex, and the three-way interaction of Time × Group × Sex. These interactions were critical for determining whether the prism intervention significantly modulated attentional networks differently over time based on the participant's sex or group assignment. The model also assessed the main effects of Group and Sex, as well as the Group × Sex interaction, to identify any baseline or global differences in attentional performance between the groups regardless of the time point.

Chapter 3. Results

3.1 Participants and Baseline Comparability

Shapiro-wilk test showed that age was normally distributed in female (W = 0.9, p = 0.06) and in males (W = 0.92, p = 0.09) while education level violated normality for both females (W = 0.77, p = .001) and males (W = 0.85, p = .007). Independent sample t-tests confirmed that female and male participants were equally matched on age (t(38) = -1.61, p = 0.12, d = -0.5) and education level (U = 168, p = 0.362, d = 0.16). Similarly, age and education level were comparable between the real and the sham groups (Age: U = 155, p = 0.222, d = 0.225; Education level: U = 164, p = 0.305, d = 0.182)

3.3. Prismatic Adaptation Results

Direct Effect

To verify the initial effect of the prisms on pointing accuracy, a 2x2 Repeated Measure ANOVA was conducted with Phase (Pre-exposure vs. Early-exposure) as the within-subjects factor and Group (Real vs. Sham) as the between-subjects factor. There was a significant main effect of Phase ($F(1,38) = 103.7$, $p < .001$, $\eta^2 = 0.3$, and a significant main effect of Group ($F(1,38) = 41.5$, $p < .001$, $\eta^2 = 0.2$). These effects were qualified by a highly significant Phase × Group interaction ($F(1,38) = 69.3$, $p < .001$, $\eta^2 = 0.2$). This interaction indicates that the groups behaved differently immediately upon putting on the glasses.

Post Hoc Comparison

To investigate the specific differences between groups and phases post-hoc test was utilized. The post-hoc analysis showed that, there was no significant difference between the Real and Sham groups during the pre-exposure phase ($t(38) = 0.04$, $p = 1.000$), confirming identical baseline accuracy. Upon entering the early-exposure phase, the Real group showed a massive and significant shift from their baseline ($t(38) = -13.08$, $p < .001$), with a mean error increase of 4.38 units. The Sham group showed no significant difference between pre-exposure and early-exposure ($t(38) = -1.31$, $p = .560$), confirming that the sham glasses did not displace their vision. Consequently, during the early-exposure phase, the pointing error of the Real group was significantly larger than that of the Sham group ($t(38) = 8.4$, $p < .001$). These findings confirm that the optical manipulation was successful. The Real prisms induced a significant visual-motor error (displacement) that was entirely absent in the Sham Group, providing the necessary conditions for adaptation to occur (see Table 3.1 and Figure 3.1).

Post Hoc Comparisons - Phase ✻ Group

Comparison					Mean Difference	SE	df	t	p_{tukey}
Phase	**Group**		**Phase**	**Group**					
Pre Exposure	**Real**	-	**Pre Exposure**	**Sham**	0.0133	0.284	38.0	0.0467	1.000
		-	**Early Exposure**	**Real**	-4.3850	0.335	38.0	-13.0888	<.001
		-	**Early Exposure**	**Sham**	-0.4267	0.389	38.0	-1.0973	0.693
	Sham	-	**Early Exposure**	**Real**	-4.3982	0.389	38.0	-11.3103	<.001
		-	**Early Exposure**	**Sham**	-0.4400	0.335	38.0	-1.3132	0.560
Early Exposure	**Real**	-	**Early Exposure**	**Sham**	3.9583	0.471	38.0	8.4034	<.001

Table 3.1. Post-hoc Comparisons for the Phase*Group Interaction across Pre and Early Exposure

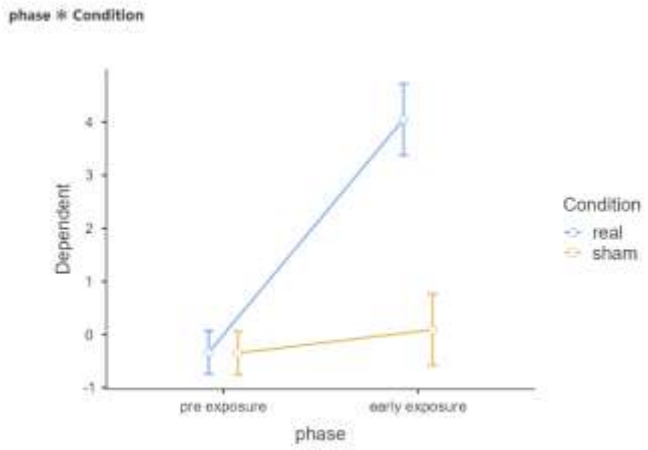

Figure 3.1. Phase*Group Interaction across Pre and Early Exposure

Y= Pointing Error (cm)

X= Phase

Adaptation

To assess the rate and extent of adaptation while wearing the prisms, a 2x2 Repeated Measure ANOVA was conducted with Phase (Early-exposure vs. Late-exposure) as the within-subjects factor and Group (Real vs. Sham) as the between-subjects factor. The analysis revealed a significant main effect of Phase ($F(1,38) = 78.4$, $p < .001$, $\eta^2 = 0.26$), and a significant main effect of Group ($F(1,38) = 58.8$, $p < .001$, $\eta^2 = 0.21$). These were further explained by a significant Phase × Group interaction ($F(1,38) = 76.6$, $p < .001$, $\eta^2 = 0.25$). This interaction suggests that the trajectory of pointing accuracy throughout the exposure period differed significantly depending on whether participants were wearing real or sham prisms.

Post Hoc Comparisons

To evaluate the learning curve within each group Post-hoc test was conducted. Analysis showed that, at the start of the exposure (Early-exposure), the Real group showed significantly higher pointing error compared to the Sham group (MD = 3.96, $t(38) = 8.4$, $p < .001$), representing the initial optical displacement. The Real group demonstrated a highly significant reduction in error from Early to Late exposure (MD = 4.19, $t(38) = 12.45$, $p < .001$). This indicates that participants successfully adapted their motor movements to compensate for the visual shift. In the Sham group, there was no significant change in pointing accuracy between Early and Late exposure (MD = 0.02, $t(38) = 0.07$, $p = 1.000$), indicating no learning was required or occurred. By the end of the exposure period (Late-exposure), the pointing accuracy of the Real group was no longer significantly different from the Sham group (MD = -0.2, $t(38) = -1.98$, $p = .213$). These results provide clear evidence of behavioral compensation. While the real prisms initially caused a significant disruption in pointing accuracy, participants were able to fully adapt by the end of the exposure phase, reaching a level of accuracy indistinguishable from the control (Sham) group. (see Table 3.2 and Figure 3.2)

Post Hoc Comparisons - Phase ✻ Group

Comparison									
Phase	**Group**		**Phase**	**Group**	**Mean Difference**	**SE**	**df**	**t**	**p_{tukey}**
Early-Exposure	**Real**	**-**	**Early-Exposure**	**sham**	3.9583	0.471	38.0	8.4034	<.001
		-	**Late-Exposure**	**Real**	4.1916	0.337	38.0	12.4500	<.001
		-	**Late-Exposure**	**Sham**	3.9832	0.341	38.0	11.6715	<.001
	Sham	**-**	**Late-Exposure**	**Real**	0.2334	0.341	38.0	0.6838	0.903
		-	**Late-Exposure**	**Sham**	0.0250	0.337	38.0	0.0741	1.000
Late-Exposure	**Real**	**-**	**Late-Exposure**	**Sham**	-0.2084	0.105	38.0	-1.9810	0.213

Table 3.2. Post-hoc Comparisons for the Phase*Group Interaction across Early and Late Exposure

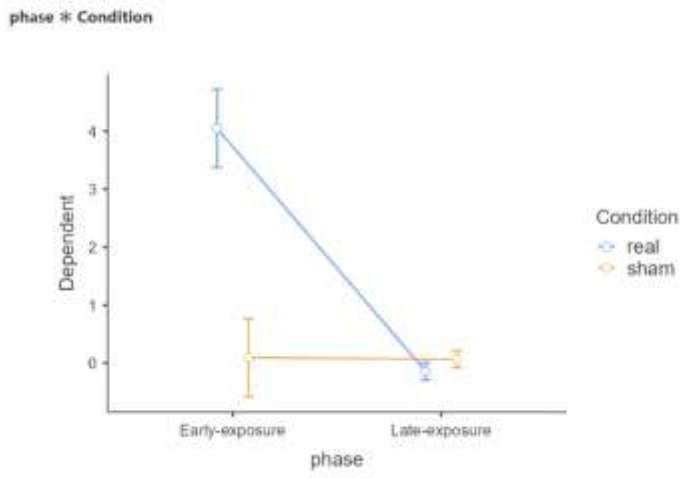

Figure 3.2. Phase*Group Interaction across Early and Late Exposure

Y= Pointing Error (cm)

X= Phase

After Effect

To investigate the presence of a prismatic aftereffect, a 2x2 Repeated Measure ANOVA was conducted with Phase (Pre-exposure invisible vs. Post-exposure invisible) as the within-subjects factor and Group (Real vs. Sham) as the between-subjects factor. The ANOVA revealed a significant main effect of Phase ($F(1,38) = 149$, $p < .001$, $\eta^2 = 0.34$), and a significant main effect of Group ($F(1,38) = 103$, $p < .001$, $\eta^2 = 0.23$). Crucially, these effects were qualified by a significant Phase × Group interaction ($F(1,38) = 107$, $p < .001$, $\eta^2 = 0.24$), indicating that the change in pointing accuracy from pre- to post-exposure differed significantly between the Real and Sham groups.

Post Hoc Comparison

To decompose the interaction, Post-hoc test was performed. At the pre-exposure phase, there was no significant difference in pointing between the Real and Sham groups (MD = 0.04, $t(38) = 1.7$, $p = .337$), confirming that both groups started at a similar baseline. The Real group showed a highly significant shift from pre-exposure to post-exposure (MD = 3.07, $t(38) = 15.92$, $p < .001$). This confirms the presence of a robust prismatic aftereffect. In contrast, the Sham group showed no significant change between pre- and post-exposure phases (MD = 0.25, $t(38) = 1.32$, $p = .555$). Following the adaptation period, the pointing accuracy of the Real group was significantly different from that of the Sham group (MD = -2.77, $t(38) = -10.28$, $p < .001$). These results demonstrate that the prismatic adaptation procedure was effective. Only the participants in the Real Group developed a significant spatial aftereffect, while the Sham Group remained stable at baseline. (see Table 3.3 and Figure 3.3)

Post Hoc Comparisons - Phase ✻ Group

Comparison								
Phase	**Group**		**Phase**	**Group**	**Mean Difference**	**SE**	**df**	**t**	**p_{tukey}**
Pre-Exposure	**Real**	-	**Pre-Exposure**	**sham**	0.0416	0.0245	38.0	1.70	0.337

Post Hoc Comparisons - Phase ✻ Group

Comparison					Mean Difference	SE	df	t	p_{tukey}
Phase	**Group**		**Phase**	**Group**					
		-	**Post-Exposure**	**Real**	3.0733	0.1930	38.0	15.92	<.001
		-	**Post-Exposure**	**Sham**	0.2967	0.1917	38.0	1.55	0.420
	Sham	-	**Post-Exposure**	**Real**	3.0316	0.1917	38.0	15.82	<.001
		-	**Post-Exposure**	**Sham**	0.2550	0.1930	38.0	1.32	0.555
Post-Exposure	**Real**	-	**Post-Exposure**	**Sham**	-2.7766	0.2700	38.0	-10.28	<.001

Table 3.3. Post-hoc Comparisons for the Phase*Group Interaction across Pre and Post Exposure

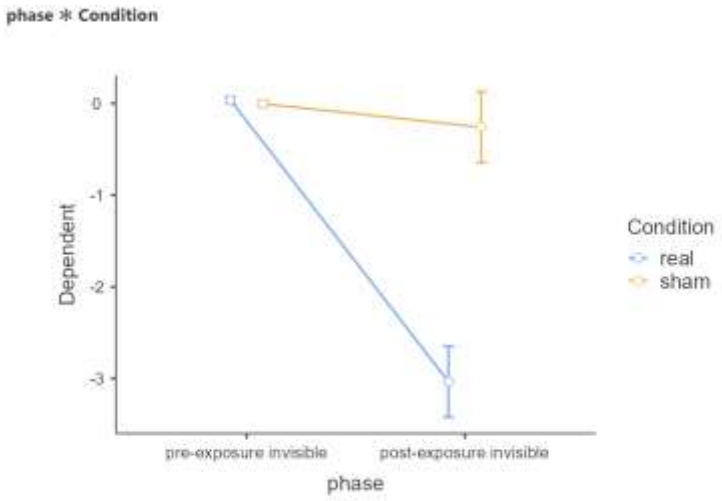

Figure 3.3. Phase*Group Interaction across Pre and Post Exposure

Y= Pointing Error (cm)

X= Phase

Persistence of the Aftereffect (15-minute Delay)

To evaluate the durability of the prismatic aftereffect following a 15-minute delay and a cognitive attention task, a 2x2 Repeated Measure ANOVA was conducted. The factors included Phase (Post-exposure invisible vs. Delayed difference-invisible) and Group (Real vs. Sham). The ANOVA revealed a significant main effect of Phase ($F(1,38) = 33.4$, $p < .001$, $\eta^2 = 0.07$), and a significant main effect of Group ($F(1,38) = 57.7$, $p < .001$, $\eta^2 = 0.44$). Importantly, a significant Phase × Group interaction was observed ($F(1,38) = 38.7$, $p < .001$, $\eta^2 = 0.09$). This indicates that the retention of the spatial shift over the 15-minute interval differed significantly between the two groups.

Post Hoc Comparisons

To analyze the stability of the aftereffect Post-hoc test was used. As established in previous phases, there was no significant difference between the Real and Sham groups at the pre-exposure baseline (MD = 0.04, $t(38) = 1.7$, $p = .337$). Even after the 15-minute delay and the intervening attention task, the Real group maintained a highly significant aftereffect compared to their baseline (MD = 1.4, $t(38) = 6.46$, $p < .001$). The Sham group showed no significant difference from baseline at the 15-minute mark (MD = 0.31, $t(38) = 1.46$, $p = .471$), confirming no spontaneous shifts occurred. In the final delayed measurement, the Real group remained significantly different from the Sham group (MD = -1.04, $t(38) = -3.43$, $p = .008$). These results demonstrate that the prismatic adaptation effect is robust and resistant to decay over short periods of time. The spatial aftereffect successfully persisted through a 15-minute delay and cognitive distraction, showing that the underlying visuo-motor reorganization was relatively stable. (see Table 3.4 and Figure 3.4)

Post Hoc Comparisons - Phase ✻ Group

Comparison					Mean Difference	SE	df	t	p_{tukey}
Phase	**Group**		**Phase**	**Group**					
Post-Exposure	**Real**	-	**Post-Exposure**	**Sham**	-2.7766	0.270	38.0	-10.285	<.001
		-	**Diff-Exposure**	**Real**	-1.6717	0.197	38.0	-8.488	<.001
		-	**Diff-Exposure**	**Sham**	-2.7150	0.288	38.0	-9.443	<.001

Post Hoc Comparisons - Phase ✻ Group

Comparison					Mean Difference	SE	df	t	p_{tukey}
Phase	**Group**		**Phase**	**Group**					
	Sham	-	**Diff-Exposure**	**Real**	1.1049	0.288	38.0	3.843	0.002
		-	**Diff-Exposure**	**Sham**	0.0617	0.197	38.0	0.313	0.989
Diff-Exposure	**Real**	-	**Diff-Exposure**	**Sham**	-1.0432	0.304	38.0	-3.431	0.008

Table 3.4. Post-hoc Comparisons for the Phase*Group Interaction across Post and Diff. Exposure

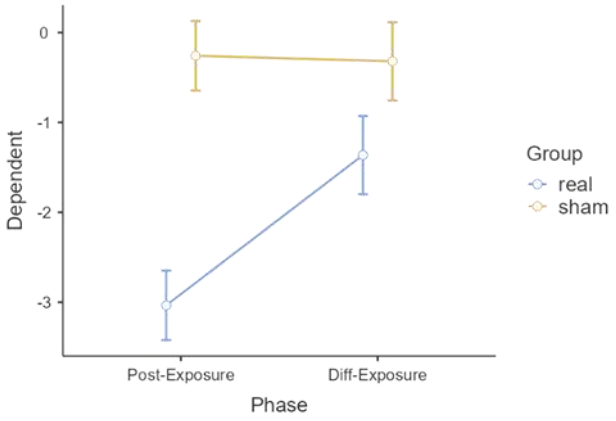

Figure 3.4. Phase*Group Interaction across Post and Diff. Exposure

Y= Pointing Error (cm)

X= Phase

3.2. Attentional Network Test (ANT) Results

Reaction Time (RT)

The analysis revealed that Reaction Times at the ANT were reduced significantly after PA in both groups (Time: $F(1,36) = 12.72$, $p = 0.001$, $\eta^2 = 0.01$). No effect of interaction between Group*Time ($F(1,36) = 0.01$, $p = 0.89$, $\eta^2 = 0$), Time*Sex ($F(1,36) = 1.37$, $p = 0.24$, $\eta^2 = 0.001$,

and Time*Group*Sex (F(1,36) = 0.05, p = 0.81, $\eta^2 = 0$) were found. Comparison between Pre-test (M = 511.506 ± 65.578) and Post-test (M = 489.893 ± 66.687) is plotted in Figure 3.5.

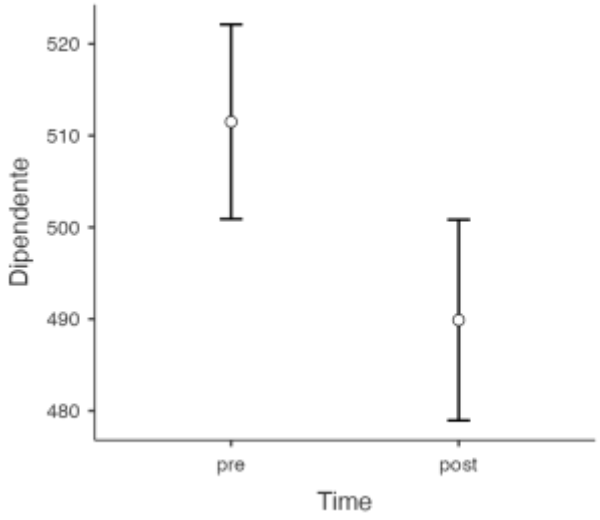

Figure 3.5. Estimated Marginal Means of Reaction Times (RT) for the Main Effect of Time.

Y= Reaction Time

X= Time

Alerting Network

Concerning the alerting subcomponent, analyses show a significant main effect of Time (F(1,36) = 10.61, p = 0.002, η^2 = 0.2) and a significant main effect of Sex (F(1,36) = 4.09, p = 0.05, η^2 = 0.03), meaning that male and females have different alerting indexes, independently from the phase of the experiment or the experimental group. No interaction between Time*Sex (F(1,36) = 0.18, p= 0.66, $\eta^2 = 0$), Time*Group (F(1,36) = 2.13, p = 11.15, $\eta^2 = 0$) or Time*Group*Sex (F(1,36) = 0, p = 0.93. $\eta^2 = 0$) emerged.

Examination of the main effect of Sex revealed that females (M = 49.2 ± 26.6) exhibited significantly higher alerting efficiency than males (M = 32.5 ± 35.5) (see Figure 3.6). This indicates that the functional benefit derived from the double-cue condition (relative to the no-cue condition) was more pronounced in the female group.

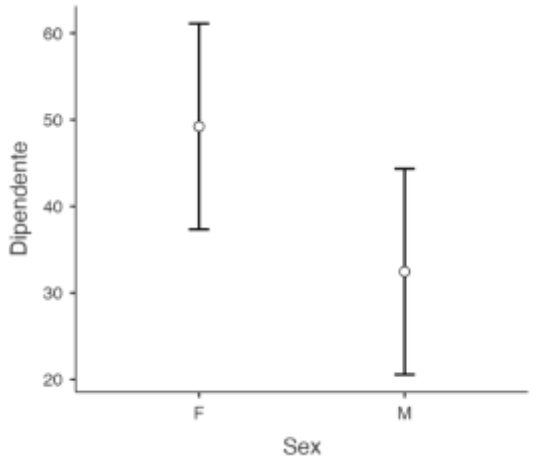

Figure 3.6. Estimated Marginal Means of the Alerting Index by Sex

Y= Alerting Index

X= Sex

Follow-up analyses showed that participants have higher alerting in post (M = 47.7 ± 30.7) than pre (M = 34 ± 28.9), independently from Group or Sex. (see Figure 3.7).

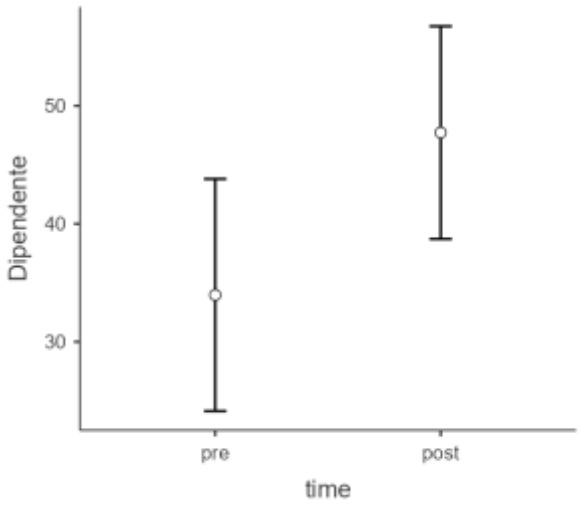

Figure 3.7. Estimated Marginal Means of the Alerting Index by Time

Y= Alerting Index

X= Time

Orienting Network

The analysis of the orienting network (based on correct trials only) revealed a significant main effect of Time ($F(1,36) = 14.8$, $p < .001$, $\eta^2 = 0.03$). This indicates a significant shift in orienting efficiency between the pre- and post-treatment sessions. No interaction in Group ($F(1,36) = 0.05$, $p = 0.82$, $\eta^2=0$) or Sex ($F(1,36) = 0$, $p = 0.94$, $\eta^2=0$) emerged. Also no interaction between Time*Sex ($F(1,36) = 0.18$, $p = 0.66$, $\eta^2=0$), Time*Group ($F(1,36) = 1.57$, $p = 0.21$, $\eta^2=0$), Time*Group*Sex ($F(1,36) = 1.75$, $p = 0.19$. $\eta^2=0$) or Group*Sex emerged ($F(1,36) = 0.49$, $p = 0.48$, $\eta^2=0$).

Results indicated that the orienting effect (calculated as RT_{center} - RT_{spatial}) was significantly greater in the pre-test (M = 27.4 ± 17.7) than in the post-test (M = 15.8 ± 20.8) (see Figure 3.8). This shift reflects a decreased sensitivity to spatial cues as the study progressed, regardless of the experimental group or participant sex.

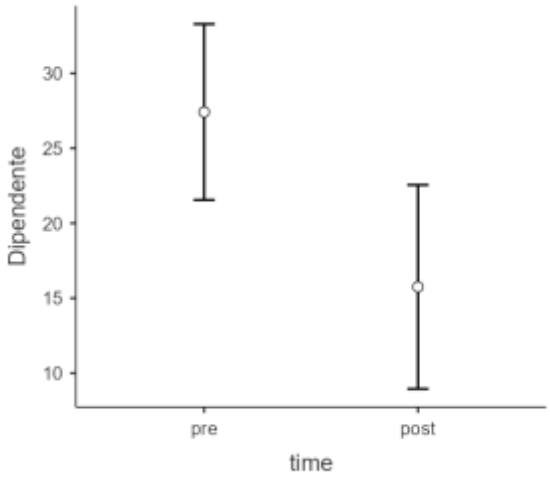

Figure 3.8. Estimated Marginal Means of the Orienting Index by Time

Y= Orienting Index

X= Time

Conflict Network

The analysis of the conflict network (executive control) revealed a significant Time*Sex interaction ($F(1,36) = 4.98$, $p = .032$, $\eta^2=0$). This indicates that the modulation of attentional

interference from pre-test to post-test differed significantly between male and female participants, regardless of the experimental group. No interaction in Time ($F(1,36) = 3.6$, $p = 0.06$, $\eta^2 = 0$) Group ($F(1,36) = 0.31$, $p = 0.58$, $\eta^2 = 0$) or Sex ($F(1,36) = 3.41$, $p = 0.07$, $\eta^2 = 0.02$ emerged. Also no interaction between Time*Sex ($F(1,36) = 4.98$, $p = 0.03$, $\eta^2 = 0$), Time*Group ($F(1,36) = 0.33$, $p = 0.56$, $\eta^2 = 0$), Time*Group*Sex ($F(1,36) = 1.62$, $p = 0.21$. $\eta^2 = 0$) or Group*Sex emerged ($F(1,36) = 0.05$, $p = 0.81$, $\eta^2 = 0$).

Follow-up post-hoc comparisons revealed that the significant interaction was driven by a distinct change in the male group. Specifically, males showed a significant difference in the conflict index between the pre-test and post-test ($t(36) = 2.92$, $p = .036$), whereas no significant change was observed for females ($t(36) = -0.85$, $p = 1.000$) (see Table 3.12). This indicates that the observed interaction between Time and Sex was primarily attributable to the performance shifts within the male population. No significant difference between Pre-test Female*Pre-test Male ($t(36) = -2.38$, $p = .136$), Pre-test Female*Post-test Female ($t(36) = -0.24$, $p = 1.000$), Pre-test Female*Post-test Male ($t(36) = -0.86$, $p = 1.000$) Pre-test Male*Post-test Female ($t(36) = 2.48$, $p = .107$), Post-test Female*Post-test Mal ($t(36) = -0.81$, $p = 1.000$) emerged.

Analysis of the conflict index for male participants revealed a significant reduction in interference from the pre-test ($M = 95.8 \pm 27.8$) to the post-test ($M = 82.2 \pm 19.1$) (see Figure 3.9).

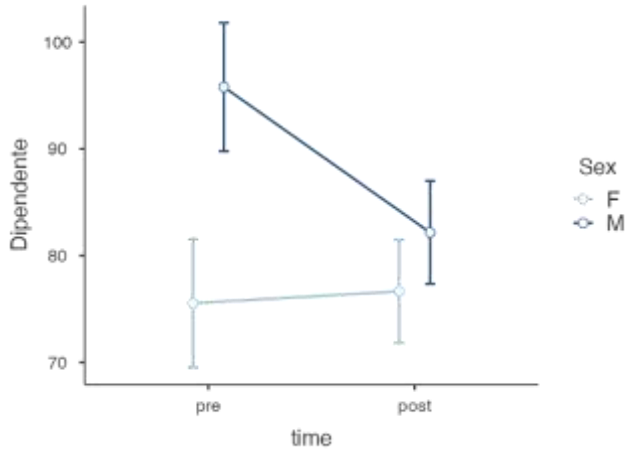

Figure 3.9. Estimated Marginal Means for the Time*Sex Interaction

Y= Conflict Index

X= Time

Error Analysis

The analysis of accuracy revealed a significant main effect of Time on error rates ($F(36) = 4.79$, $p = .035$, $\eta^2=0.01$). This indicates a significant modulation in the number of errors committed by participants between the pre-test and post-test sessions, regardless of sex or experimental group. No interaction in Group ($F(1,36) = 2.09$, $p= 0.15$, $\eta^2=0.01$) or Sex ($F(1,36) = 0.15$, $p= 0.69$, $\eta^2=0$) emerged. Also no interaction between Time*Sex ($F(1,36) = 0.03$, $p= 0.84$, $\eta^2=0$), Time*Group ($F(1,36) = 0.24$, $p = 0.62$, $\eta^2=0$), Time*Group*Sex ($F(1,36) = 0.92$, $p = 0.34$, $\eta^2=0$) or Group*Sex emerged ($F(1,36) = 0.43$, $p = 0.51$, $\eta^2=0$).

Interestingly, the significant main effect of Time ($F(36) = 4.79$, $p = .035$) revealed that participants across all groups committed more errors during the post-test ($M = 4.50 \pm 4.09$) than in the pre-test ($M = 3.07 \pm .03$) (see Figure 3.10). This increase in error rates, occurring alongside the faster reaction times observed previously, suggests a speed-accuracy trade-off or a possible fatigue effect as the experiment progressed.

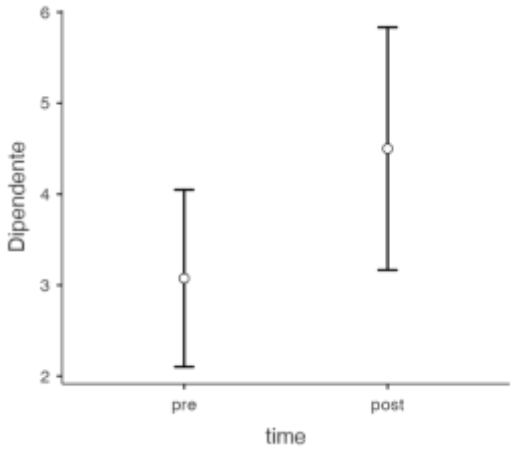

Figure 3.10. Estimated Marginal Means of the Error Index by Time

Y= Error Index

X= Time

Chapter 4. Discussion

4.1 Main Findings

The present study investigated whether Prismatic Adaptation would improve higher-level attentional processing, such as Executive Control, Orienting, and Alerting, in healthy individuals. We specifically aimed to analyze how attentional components differ between men and women. The results, however, revealed a more complex reality: while the intervention was highly effective at inducing robust sensorimotor adaptation, it did not produce the anticipated group-specific cognitive transfer. Instead, observed modulations in attentional performance were largely driven by task repetition and sex-based differences rather than the prismatic intervention itself.

The success of the sensorimotor component of our study is clear; the experimental manipulation effectively induced spatial realignment. Consistent with the three-stage adaptation process, the Real PA group exhibited a significant initial pointing error (direct effect) compared to the Sham group. This massive error reflects an immediate disruption of the visual-motor loop, a phenomenon described by Michel (2016) as a demonstration of sensorimotor plasticity, which allows the brain to produce appropriate motor responses in reaction to environmental changes. Over the course of the exposure phase, our participants successfully recalibrated their movements to compensate for the 10° visual shift. As described by Redding and Wallace (2002), this rapid reduction in pointing error is driven by calibration, a high-level, strategic, and attention-driven process in which the brain utilizes associative learning to consciously adjust future movements based on immediate past failures.

Crucially, the Real group developed a robust spatial aftereffect that persisted even after a 15-minute delay and an intervening cognitive task. This aligns with the framework established by Redding and Wallace (1997), who emphasize that spatial realignment serves as the true "core" of prism adaptation and is the primary driver of global aftereffects (Redding & Wallace, 1997). As Redding et al. (2005) further clarify, strategic calibration alone is highly context-specific and does not produce lasting aftereffects; it is the underlying alignment process that makes adaptation durable (Redding et al., 2005a). Alignment involves the automatic, transparent computation of coordinate systems mediated by the cerebellum. As Templeton, Howard, and Wilkinson (1974) demonstrated in their foundational work on the additivity of these components, the adaptation

process is not a unitary change but rather the cumulative effect of proprioceptive changes in the trained arm and shifts in the eye-head system (Templeton et al., 1974). Because our participants exhibited a significant aftereffect despite the delay and the intervening ANT, we assume that based on the assertion by Redding and Wallace (1993), true spatial realignment occurred. This realignment is a form of non-associative learning in which the brain fundamentally updates its sensorimotor coordinate constants across the entire spatial reference frame. Despite this successful behavioral adaptation, the lack of specific effect on the attentional networks suggests that in healthy systems, such sensorimotor realignment may operate independently of the higher-level cognitive executive networks measured here.

Despite the successful sensorimotor adaptation, the data did not support the improvement of the higher-level attention hypothesis in this healthy sample. While reaction times (RT) decreased from pre-test to post-test, this improvement was observed in both the Real and Sham groups, accompanied by a significant increase in error rates across all participants. Furthermore, while we identified distinct sex differences in the Alerting and Executive Control networks, these modulations occurred independently of the PA intervention. The observed pattern of faster RTs paired with higher error rates proposes a speed-accuracy trade-off or general task-related fatigue rather than a PA-induced cognitive enhancement. According to the framework established by Fan et al. (2002), the ANT is designed to isolate the efficiency of three independent attentional systems; however, our results indicate that in healthy, intact brains, these systems may not be susceptible to the same "bottom-up" modulation that benefits patients with clinical deficits. Although Prism Adaptation (PA) is known to engage the Dorsal Attention Network (DAN) during attentional tasks, it did not lead to improved executive performance in our study. This suggests that PA may modulate different neural networks than those specifically assessed by the Attention Network Test (ANT), or that a single session of PA is simply insufficient to produce measurable cognitive improvements.

The results regarding Alerting Network demonstrated that females exhibited significantly higher alerting efficiency than males, indicating increased vigilance in response to preparatory signals. However, this result is regardless of time (pre/post) and group (real/sham). When contextualizing this finding against existing research, the literature presents a complex picture. Liu et al. (2013), in their study of healthy young adults, reported no significant sex differences in alerting efficiency.

This recommends that under standard, non-pathological conditions, the brain's ability to maintain a state of high alertness, the tonic readiness to respond to incoming stimuli, may not inherently differ by sex (Liu et al., 2013). This is further supported by Urbanek et al. (2010), who, while identifying sex-specific alterations in the executive network in patients with schizophrenia, observed no such divergence in the alerting or orienting networks within their healthy control groups (Urbanek et al., 2010). However, our observation that females derive a more pronounced benefit from warning signals aligns with more recent, population-specific research. Facci et al. (2025) found that sex-based differences in attentional functioning, including executive control, become more distinct in specific cohorts, such as healthy older adults or those with mild cognitive impairment (MCI), where sex-based compensatory strategies likely influence network performance (Facci et al., 2025a). The variability in these findings is further underscored by Kim et al. (2025); in their pilot study utilizing specific rhythm auditory stimulation, they found no sex-based differences across any ANT variables, including alerting (Kim et al., 2025). This suggests that the "alerting advantage" observed in our female participants may not represent a generalized, fixed sex difference. Instead, as posited by the foundational framework of Posner and Rothbart (2007), the alerting network is a dynamic, localized system (Posner & Rothbart, 2007). Our findings, in the context of the cited studies, imply that the efficiency of this network is highly sensitive to the experimental protocol (e.g., visual-cue structure vs. rhythmic auditory stimulation), participant age, and the underlying cognitive strategies (such as tonic versus phasic alertness) recruited to maintain readiness under task demands.

Regarding Orienting Network, contrary to the hypothesis that females would show greater improvement in orienting due to a more responsive system, orienting efficiency decreased for all participants across time. There were no sex differences observed here. This overall shift reflects a generalized decrease in sensitivity to spatial cues as the task progressed. The most straightforward explanation for this, is cognitive fatigue. The ANT is a high-demand task that requires sustained attention and rapid motor responses. Maintaining peak attentional performance over repeated testing blocks (pre-test, PA exposure, 15-minute delay, and post-test) depletes the brain's attentional energy. Furthermore, as the experiment progresses, participants' motivation often wanes, leading to a natural decline in the arousal necessary to maintain high orienting efficiency. This is a common occurrence in long cognitive batteries, where the "freshness" of the first session

is impossible to replicate in the second. Even after a 15-minute rest, the brain may still be in a state of post-adaptation stabilization, where the executive and attentional resources required to maintain the new spatial map conflict with the resources needed to perform the high-speed spatial orienting required by the ANT (Martín-Arévalo et al., 2016; Taylor & Thoroughman, 2008). Furthermore, the ANT is inherently repetitive. By the time participants reach the post-test, they have been exposed to the same cues repeatedly, which can lead to habituation and a vigilance decrement where attention wanes for predictable stimuli (Luna et al., 2023). Consequently, by the post-test, the spatial cues in the ANT may no longer elicit the same novelty response in the orienting network that they did during the pre-test. Orienting relies on the brain's ability to prioritize new spatial information; if the brain habituates to the spatial cues as constant and predictable, it may reduce the neural effort dedicated to orienting toward them, which manifests behaviorally as a decrease in sensitivity (Luna et al., 2023). Finally, individual differences must be considered, as studies suggest that biological sex significantly influences the efficiency of the orienting network during the ANT. Specifically, Liu et al. (2013) observed that females demonstrated higher orienting scores compared to males, proposing that females may exhibit faster covert orienting of attention to spatially cued locations (Liu et al., 2013). This suggests a potential sex-based advantage in the engagement or disengagement mechanisms of the orienting network. Conversely, other research highlights that these differences are not universal and may depend on the testing environment or the clinical profile of the subjects. For instance, studies examining healthy older adults or patients with mild cognitive impairment (MCI) have reported no significant sex differences in orienting efficiency (Facci et al., 2025b). Further literature suggests that when the ANT is modified, for example, by using auditory stimuli, no sex-based differences are observed for any ANT variable, including the orienting network. This supports the notion that sex-based disparities in attention may be specific to visual-spatial processing rather than generalized attentional mechanisms. The inconsistency in findings often points to the distinction between structural neural differences and strategic deployment of attention. While Posner and Petersen (2012) define the orienting network by its capacity to prioritize input by selecting a modality or location, Fan et al. (2002) emphasize that performance on the ANT is a result of both network efficiency and individual strategy (Fan et al., 2002; Petersen & Posner, 2012). Differences in how males and females navigate spatial cues may reflect distinct strategies in processing speed or impulsivity, as discussed by Riley et al. (2016)

and Conners et al. (2003), rather than a fundamental difference in the "hard-wiring" of the orienting circuit itself (Conners et al., 2003; Riley et al., 2016).

The literature regarding executive control has historically been controversial, with conflicting reports on interference susceptibility between sexes. The present study found a significant Time × Sex interaction within the conflict network. Males demonstrated a significant reduction in interference (improved conflict resolution) from pre-test to post-test, whereas females showed no significant change. However, because this occurred independently of the experimental group, it cannot be attributed to PA. Instead, it highlights distinct sex-specific practice effects or neural response strategies. As noted by Riley et al. (2016) and Conners et al. (2003), males and females often deploy different strategies regarding impulsivity, processing speed, and inhibitory control during continuous performance tasks (Conners et al., 2003; Riley et al., 2016). This variance is further contextualized by Urbanek et al. (2009), who identified sex specific alterations of executive function using the ANT, suggesting that while basic attentional networks might be stable, the executive control network is highly sensitive to resolving conflicting stimuli (Urbanek et al., 2009). Similarly, recent findings from Facci et al. (2025) indicate that when assessing executive control in healthy and clinical populations, the efficiency of the conflict network is not uniform; sex-based performance differences frequently emerge as a result of varying compensatory cognitive strategies, particularly as task demands increase (Facci et al., 2025b). Posner and DiGirolamo (1998) identify the anterior cingulate gyrus as central to conflict resolution, but our results align with the broader literature to suggest a more nuanced view. Specifically, the modulation of this executive network depends on individual response strategies and sex-specific baseline approaches to inhibitory control, rather than sensorimotor plasticity driven by prism exposure (Posner & DiGirolamo, 1998).

4.2 Limitations of the Study

Several limitations should be considered when interpreting these results. First, the primary limitation is the evident speed-accuracy trade-off or fatigue effect observed during the post-test ANT, characterized by faster response times but significantly higher error rates across the entire sample. This generalized testing effect, driven by the repetitive nature of the ANT and the mental

effort required by the prism task, likely obscured any subtle cognitive improvements produced by the intervention. In their critical appraisal of the ANT, MacLeod et al. (2010) noted that the test's reliance on rapid, repeated trials makes it highly sensitive to fluctuations in arousal and motivation. This sensitivity can inadvertently obscure the detection of small, intervention-specific effect sizes in healthy participants (MacLeod et al., 2010).

Secondly, future studies might benefit from a more proximal post-test or the use of neurophysiological markers, such as fMRI or EEG, to capture transient neural shifts that behavioral performance metrics, constrained by speed-accuracy trade-offs, might fail to reflect.

Another significant limitation of the present study is that we did not control for or record the menstrual cycle phase of our female participants. Research has demonstrated that the efficiency of inhibitory and attentional control is not a static trait but fluctuates significantly with hormonal changes. For instance, Colzato et al. (2012) found that estrogen levels actively modulate inhibitory input control; specifically, women exhibited a significantly more pronounced Inhibition of Return (IOR) effect during their follicular phase, which is associated with higher estradiol levels and increased dopamine turnover rates, compared to their luteal or menstruation phases (Colzato et al., 2012). Notably, this increase in women's IOR during the follicular phase was also greater than the effect found for men at any phase. This evidence suggests that gender differences in inhibitory control are variable and state-dependent rather than structurally fixed. The networks assessed by the ANT, particularly the alerting and executive control networks, rely heavily on similar dopaminergic pathways. Given this shared reliance, it is highly plausible that the sex differences observed in our data, such as the heightened alerting efficiency in females, may have been influenced by unrecorded hormonal states. Future research should account for this variability by incorporating non-invasive hormonal tracking, such as salivary estradiol assessments, to better isolate the specific cognitive effects of sensorimotor plasticity from natural hormonal fluctuations.

Finally, as an additional theoretical consideration when interpreting the lack of specific cognitive transfer, it is worth acknowledging the potential influence of a "ceiling effect". Prism adaptation is primarily established as a therapeutic tool that successfully rebalances a severely impaired spatial reference frame in patients with profound neurological deficits, such as Unilateral Spatial Neglect. While it is a scientifically sound and promising endeavor to explore whether this mechanism can be extended to enhance higher-order attention in healthy individuals, measuring

such improvements can be challenging. Young, highly educated adults typically possess attentional networks that are already functioning at a high, optimal baseline. Because their baseline performance is naturally near the maximum possible level, there may be limited room for further measurable enhancement, even following robust sensorimotor plasticity. This perspective aligns with Michel's (2016) observation that while the "cognitive expansion" of PA is an exciting area of research, its underlying mechanisms are highly variable and may manifest less potently in neural systems that are not inherently dysfunctional.

4.3 Future Directions

Future research on the sensorimotor plasticity should design experiments that clearly separate 'practice and fatigue effects' (such as improvements or declines simply due to repeated testing) from the true effects of the prism intervention. Using alternative cognitive assessments less prone to rapid task learning, or spacing the pre- and post-tests further apart, may help clarify these dynamics. Furthermore, because healthy individuals already perform at a high level, standard behavioral metrics might not capture the full picture. Since sex-dependent neural activation patterns can exist even when behavioral outcomes appear identical, future studies should include brain imaging tools, such as EEG or fMRI. This approach could uncover hidden changes in brain activity and reveal how men and women might differentially recruit the Default Mode Network or Dorsal Attention Network following prismatic adaptation. Finally, future clinical applications of PA should continue to consider patient sex, as the distinct resting-state and task-activated strategies used by men and women may interact differently with sensorimotor rehabilitation.

Chapter 5. Conclusion

It is well-established that prism adaptation (PA) is a non-invasive technique widely researched and used for its clinical utility to treat Unilateral Spatial Neglect (USN), a debilitating condition typically occurring after a right-hemisphere stroke. However, its effect on attentional networksm which play a crucial role in supporting a wide range of high-level cognitive functions in healthy people, remains not fully understood. Specifically, biological sex has received limited attention in

prior studies, despite increasing recognition of its potential role in cognitive function. To the best of our knowledge, no previous study has investigated the impact of sex on attentional functioning in the context of using Prismatic Adaptation glasses. Therefore, a primary goal of this research is to determine whether PA mechanisms can influence higher-order attentional networks, including Alerting, Orienting, and Executive Control, in healthy individuals. More importantly, there is a clear gap in the literature because no previous studies have investigated how the effect of PA on attention might differ between healthy men and women, and also, existing studies on sex differences in attention at baseline, regardless of PA intervention, often report mixed results. To address this gap, our experiment measured attentional performance before and after PA exposure. We investigated whether sensorimotor plasticity yields different cognitive effects by biological sex, aiming to better understand its role in modulating attention.

To ensure the reliability of our findings, we utilized the Attention Network Test (ANT), for detecting changes in specific attentional functions. We compared a real PA group with a sham control group to confirm that any observed changes were truly caused by the prismatic intervention and not simply by practicing the task. Furthermore, by carefully matching the participants in both groups for age and education level, we minimized the influence of external demographic variables on cognitive performance. To avoid biased comparisons, our analysis focused strictly on the corrected scores for the Alerting, Orienting, and Executive Control networks. This rigorous methodological approach allowed us to confidently evaluate the true impact of sensorimotor adaptation on these attention networks. Our results confirmed that the experimental protocol was highly effective in inducing sensorimotor plasticity, consistent with the expected pattern reported in the Prismatic Adaptation literature. The Real PA group demonstrated a significant initial pointing error, followed by successful behavioral compensation and a robust spatial aftereffect that persisted despite a 15-minute delay and an intervening cognitive task. This provides clear evidence that the prismatic intervention triggered a neural reorganization of internal spatial maps, consistent with the fundamental mechanisms of sensorimotor alignment. However, the hypothesis that this sensorimotor realignment would transfer to higher-level attentional networks was not supported. While improvements in reaction times were observed across the entire sample, they were accompanied by increased error rates, suggesting a generalized speed-accuracy trade-off or task-related fatigue rather than a PA-induced cognitive enhancement. Consequently, we concluded that in healthy systems where attentional networks are already functioning at an optimal baseline, the

sensorimotor modulation provided by PA does not readily translate into enhanced executive performance. While other studies demonstrated that PA's ability to modulate attentional networks is primarily effective in clinical populations with visuospatial deficits, such as those with Unilateral Spatial Neglect, our study suggests that it does not have effect on healthy individuals. Our work contributed to the literature by challenging the assumption that sensorimotor recalibration automatically transfers to non-spatial cognitive domains in healthy individuals. It highlights a functional boundary between the cerebellar-mediated alignment processes and the high-level attentional networks. These findings are critical for clinicians and researchers considering PA as an intervention. Our study suggests that, because a single PA experimental session was insufficient to elicit consistent cognitive outcomes in all healthy individuals, a uniform response to this intervention should not be expected. Consequently, applying a standardized, equal intervention for all participants may be inherently ineffective. Instead, clinical protocols must be highly individualized, potentially requiring different numbers of intervention sessions tailored to people's specific cognitive profiles and needs to achieve an outcome.

Regarding the role of sex, while we identified distinct attentional profiles, notably a female advantage in the Alerting network and a significant practice effect in conflict resolution within the male group, these modulations occurred independently of the prismatic intervention. This finding contrasts with our initial hypothesis, which posited that sensorimotor plasticity would differentially modulate these networks based on biological sex. Specifically, we hypothesized that females would show greater improvement in the orienting network, whereas males would show greater improvement in the executive control network, due to distinct activation of the cerebello-parietal loop. These findings underscore the influence of sex specific cognitive strategies and individual task approach on attentional performance, rather than a sex-dependent response to sensorimotor plasticity.

Chapter 6. Acknowledgments

First and foremost, I would like to express my sincere gratitude to my supervisor and co-supervisor, Prof. Dr. Martina Gandola and Dott.ssa Laura Facci, for their invaluable guidance, patience, and continuous support throughout my master’s degree. Their insightful feedback and

expertise in refining my experimental design and navigating the complexities of cognitive neuroscience were instrumental in shaping this thesis.

I would also like to thank Dott.ssa Laura Sandirini for their time, valuable perspectives and practical advice on this work. A special thank you to the technical staff for their assistance, and to all the participants who generously volunteered their time for this study.

Chapter 7. References

Akshoomoff, N. A., Courchesne, E., & Townsend, J. (1997). Attention coordination and anticipatory control. *International Review of Neurobiology*, *41*, 575–598.

Anderson, V. (2001). Assessing executive functions in children: Biological, psychological, and developmental considerations. *Pediatric Rehabilitation*, *4*(3), 119–136. https://doi.org/10.1080/13638490110091347

Anderson, V. A., Anderson, P., Northam, E., Jacobs, R., & Catroppa, C. (2001). Development of Executive Functions Through Late Childhood and Adolescence in an Australian Sample. *Developmental Neuropsychology*, *20*(1), 385–406. https://doi.org/10.1207/S15326942DN2001_5

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, *8*(4), 170–177.

Astur, R. S., Ortiz, M. L., & Sutherland, R. J. (1998). A characterization of performance by men and women in a virtual Morris water task: A large and reliable sex difference. *Behavioural Brain Research*, *93*(1–2), 185–190.

Baron, G., Danesin, L., Ranzini, M., Menardi, A., Vallesi, A., Bonato, M., Oliveri, M., Semenza, C., Bottini, G., & Burgio, F. (2025). Repetitive exposure to prismatic adaptation in post-stroke optic ataxia: A single case study exploring behavioural changes and brain functional reorganization. *NeuroImage*, *323*, 121573. https://doi.org/10.1016/j.neuroimage.2025.121573

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48.

Bedford, F. L. (1993). Perceptual and cognitive spatial learning. *Journal of Experimental Psychology: Human Perception and Performance*, *19*(3), 517.

Berger, A., & Posner, M. I. (2000a). Pathologies of brain attentional networks. *Neuroscience and Biobehavioral Reviews*, *24*(1), 3–5. https://doi.org/10.1016/s0149-7634(99)00046-9

Berger, A., & Posner, M. I. (2000b). Pathologies of brain attentional networks. *Neuroscience and Biobehavioral Reviews*, *24*(1), 3–5. https://doi.org/10.1016/s0149-7634(99)00046-9

Bingham, G., & Romack, J. L. (1999). The rate of adaptation to displacement prisms remains constant despite acquisition of rapid calibration. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(5), 1331.

Bisiach, E., & Luzzatti, C. (1978). Unilateral neglect of representational space. *Cortex*, *14*(1), 129–133.

Caffarra, P., Vezzadini, G., Zonato, F., Copelli, S., & Venneri, A. (2003). A normative study of a shorter version of Raven's progressive matrices 1938. *Neurological Sciences: Official Journal of the Italian Neurological Society and of the Italian Society of Clinical Neurophysiology*, *24*(5), 336–339. https://doi.org/10.1007/s10072-003-0185-0

Christakou, A., Halari, R., Smith, A. B., Ifkovits, E., Brammer, M., & Rubia, K. (2009). Sex-dependent age modulation of frontostriatal and temporo-parietal activation during cognitive control. *Neuroimage*, *48*(1), 223–236.

Clayson, P. E., Clawson, A., & Larson, M. J. (2011). Sex differences in electrophysiological indices of conflict monitoring. *Biological Psychology*, *87*(2), 282–289.

Collette, F., Hogge, M., Salmon, E., & Van der Linden, M. (2006). Exploration of the neural substrates of executive functioning by functional neuroimaging. *Neuroscience*, *139*(1), 209–221.

Collins, D. W., & Kimura, D. (1997). A large sex difference on a two-dimensional mental rotation task. *Behavioral Neuroscience*, *111*(4), 845.

Coll-Martín, T., Carretero-Dios, H., & Lupiáñez, J. (2021). Attentional networks, vigilance, and distraction as a function of attention-deficit/hyperactivity disorder symptoms in an adult community sample. *British Journal of Psychology (London, England: 1953)*, *112*(4), 1053–1079. https://doi.org/10.1111/bjop.12513

Colzato, L. S., Pratt, J., & Hommel, B. (2012). Estrogen modulates inhibition of return in healthy human females. *Neuropsychologia*, *50*(1), 98–103. https://doi.org/10.1016/j.neuropsychologia.2011.11.003

Conners, C. K., Epstein, J. N., Angold, A., & Klaric, J. (2003). Continuous Performance Test Performance in a Normative Epidemiological Sample. *Journal of Abnormal Child Psychology*, *31*(5), 555–562. https://doi.org/10.1023/A:1025457300409

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: From environment to theory of mind. *Neuron*, *58*(3), 306–324.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 201–215.

Coull, J. T., & Nobre, A. C. (1998). Where and when to pay attention: The neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *Journal of Neuroscience*, *18*(18), 7426–7435.

Craske, B., & Crawshaw, M. (1975). Oculomotor adaptation to prisms is not simply a muscle potentiation effect. *Perception & Psychophysics*, *18*(2), 105–106. https://doi.org/10.3758/BF03204095

Cykowski, M. D., & Masdeu, J. C. (2025). The cholinergic basal forebrain and its role in neurodegeneration. *Journal of Neuropathology and Experimental Neurology*, *84*(12), 1073–1093. https://doi.org/10.1093/jnen/nlaf112

Dabbs Jr, J. M., Chang, E.-L., Strong, R. A., & Milun, R. (1998). Spatial ability, navigation strategy, and geographic knowledge among men and women. *Evolution and Human Behavior*, *19*(2), 89–98.

De Bellis, M. D., Keshavan, M. S., Beers, S. R., Hall, J., Frustaci, K., Masalehdan, A., Noll, J., & Boring, A. M. (2001). Sex differences in brain maturation during childhood and adolescence. *Cerebral Cortex*, *11*(6), 552–557.

De Luca, C. R., Wood, S. J., Anderson, V., Buchanan, J.-A., Proffitt, T. M., Mahony, K., & Pantelis, C. (2003). Normative Data From the Cantab. I: Development of Executive Function Over the Lifespan. *Journal of Clinical and Experimental Neuropsychology*, *25*(2), 242–254. https://doi.org/10.1076/jcen.25.2.242.13639

Dewar, R. (1971). Adaptation to displaced vision: Variations on the "prismatic-shaping" technique. *Perception & Psychophysics*, *9*(2), 155–157. https://doi.org/10.3758/BF03212619

Dumais, K. M., Chernyak, S., Nickerson, L. D., & Janes, A. C. (2018a). Sex differences in default mode and dorsal attention network engagement. *PloS One*, *13*(6), e0199049.

Dumais, K. M., Chernyak, S., Nickerson, L. D., & Janes, A. C. (2018b). Sex differences in default mode and dorsal attention network engagement. *PloS One*, *13*(6), e0199049.

Ebenholtz, S. M. (1974). The Possible Role of Eye-Muscle Potentiation in Several Forms of Prism Adaptation. *Perception*, *3*(4), 477–485. https://doi.org/10.1068/p030477

Elston, T. W., & Bilkey, D. K. (2017). *Neural correlate of relief in the anterior cingulate cortex and ventral tegmental area: Neural correlate of relief in the ACC and VTA* (p. 102178). bioRxiv. https://doi.org/10.1101/102178

Evans, K. L., & Hampson, E. (2015). Sex-dependent effects on tasks assessing reinforcement learning and interference inhibition. *Frontiers in Psychology*, *6*, 1044.

Everitt, B. J., Robbins, T. W., & Muir, J. L. (1995). Reversal of visual attentional dysfunction following lesions of the cholinergic basal forebrain by physostigmine and nicotine but not by the 5-HT3 receptor antagonist, ondansetron. *Psychopharmacology*, *118*(1), 82–92.

Facci, L., Sandrini, L., & Bottini, G. (2025a). Attentional functioning in healthy older adults and aMCI patients: Results from the Attention Network Test with a focus on sex differences. *Brain Sciences*, *15*(7), 770.

Facci, L., Sandrini, L., & Bottini, G. (2025b). Attentional functioning in healthy older adults and aMCI patients: Results from the Attention Network Test with a focus on sex differences. *Brain Sciences*, *15*(7), 770.

Fan, J., Gu, X., Guise, K. G., Liu, X., Fossella, J., Wang, H., & Posner, M. I. (2009). Testing the behavioral interaction and integration of attentional networks. *Brain and Cognition*, *70*(2), 209–220. https://doi.org/10.1016/j.bandc.2009.02.002

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347. https://doi.org/10.1162/089892902317361886

Fan, J., Mccandliss, B., Fossella, J., Flombaum, J., & Posner, M. (2005). The activation of attentional networks. *NeuroImage*, *26*(2), 471–479. https://doi.org/10.1016/j.neuroimage.2005.02.004

Fan, J., & Posner, M. (2004). Human attentional networks. *Psychiatrische Praxis*, *31 Suppl 2*, S210-214. https://doi.org/10.1055/s-2004-828484

Foote, S. L., Bloom, F. E., & Aston-Jones, G. (1983). Nucleus locus ceruleus: New evidence of anatomical and physiological specificity. *Physiological Reviews*, *63*(3), 844–914. https://doi.org/10.1152/physrev.1983.63.3.844

Foote, S. L., Freedman, R., & Oliver, A. P. (1975). Effects of putative neurotransmitters on neuronal activity in monkey auditory cortex. *Brain Research*, *86*(2), 229–242.

Forte, G., Favieri, F., Marotta, A., Arcari, L., Cacciotti, L., & Casagrande, M. (2024). The Efficiency of Attentional Networks in Takostubo Syndrome: A Study With the Attentional Network Task for Interaction. *Journal of Attention Disorders*, *28*(4), 469–479. https://doi.org/10.1177/10870547231215517

Frassinetti, F., Angeli, V., Meneghello, F., Avanzi, S., & Làdavas, E. (2002). Long-lasting amelioration of visuospatial neglect by prism adaptation. *Brain*, *125*(3), 608–623.

Friedrich, F. J., Egly, R., Rafal, R. D., & Beck, D. (1998). Spatial attention deficits in humans: A comparison of superior parietal and temporal-parietal junction lesions. *Neuropsychology*, *12*(2), 193.

Gang, L. I. U., Jin, F. A. N., & Kai, W. (2013). Gender differences associated with orienting attentional networks in healthy subjects. *Chinese Medical Journal*, *126*(12), 2308–2312.

Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., Paus, T., Evans, A. C., & Rapoport, J. L. (1999). Brain development during childhood and adolescence: A longitudinal MRI study. *Nature Neuroscience*, *2*(10), 861–863.

Grahn, J., Parkinson, J., & Owen, A. (2008). The cognitive functions of the caudate nucleus. *Progress in Neurobiology*, *86*, 141–155. https://doi.org/10.1016/j.pneurobio.2008.09.004

Guigon, E., & Baraduc, P. (2002). A neural model of perceptual-motor alignment. *Journal of Cognitive Neuroscience*, *14*(4), 538–549.

Gur, R. E., Turetsky, B. I., Bilker, W. B., & Gur, R. C. (1999). Reduced gray matter volume in schizophrenia. *Archives of General Psychiatry*, *56*(10), 905–911.

Harris, C. S. (1963). *Adaptation to displaced vision: A proprioceptive change* [PhD Thesis]. Harvard University.

Harris, C. S. (1974). Beware of the Straight-Ahead Shift—A Nonperceptual Change in Experiments on Adaptation to Displaced Vision. *Perception*, *3*(4), 461–476. https://doi.org/10.1068/p030461

Hay, J. C., Pick, H. L., & Ikeda, K. (1965). Visual capture produced by prism spectacles. *Psychonomic Science*, *2*(1–12), 215–216. https://doi.org/10.3758/BF03343413

Held, R., & Freedman, S. J. (1963). Plasticity in Human Sensorimotor Control: Studies of disordered motor-sensory feedback raise questions about man's coordination in outer space. *Science*, *142*(3591), 455–462. https://doi.org/10.1126/science.142.3591.455

Helmholtz, H. L. F. von, & Southall, J. P. C. (1925). Treatise on physiological optics. *(No Title)*. https://cir.nii.ac.jp/crid/1130282272156580352

Heyder, K., Suchan, B., & Daum, I. (2004). Cortico-subcortical contributions to executive control. *Acta Psychologica*, *115*(2–3), 271–289.

Jakobson, L. S., & Goodale, M. A. (1989). Trajectories of reaches to prismatically-displaced targets: Evidence for "automatic" visuomotor recalibration. *Experimental Brain Research*, *78*(3), 575–587.

James, W. (1890). *The Principles of Psychology New York: Dover*.

Jeannerod, M., & Rossetti, Y. (1993). Visuomotor coordination as a dissociable visual function: Experimental and clinical evidence. *Baillieres Clin Neurol*, *2*(2), 439–460.

John, & Raven, J. (2003). Raven Progressive Matrices. In R. S. McCallum (Ed.), *Handbook of Nonverbal Assessment* (pp. 223–237). Springer US. https://doi.org/10.1007/978-1-4615-0153-4_11

Kim, A. R., Kim, J. W., Kim, N. Y., & Kang, D. W. (2025). Specific rhythm auditory stimulation for attention: A pilot randomized controlled trial. *Clinical Psychopharmacology and Neuroscience*, *23*(2), 286.

Kitazawa, S., Kimura, T., & Uka, T. (1997). Prism adaptation of reaching movements: Specificity for the velocity of reaching. *Journal of Neuroscience*, *17*(4), 1481–1492.

Klenberg, L., Korkman, M., & Lahti-Nuuttila, P. (2001). Differential Development of Attention and Executive Functions in 3- to 12-Year-Old Finnish Children. *Developmental Neuropsychology*, *20*(1), 407–428. https://doi.org/10.1207/S15326942DN2001_6

KM, H. (1985). Neglect and related disorders. *Clinical Neurophysiology*. https://cir.nii.ac.jp/crid/1573950399673823744

Langener, A. M., Kramer, A., van den Bos, W., & Huizenga, H. M. (2022). A shortened version of Raven's standard progressive matrices for children and adolescents. *The British Journal of Developmental Psychology*, *40*(1), 35–45. https://doi.org/10.1111/bjdp.12381

Liu, K., Sun, G., Li, B., Jiang, Q., Yang, X., Li, M., Li, L., Qian, S., Zhao, L., & Zhou, Z. (2013). The impact of passive hyperthermia on human attention networks: An fMRI study. *Behavioural Brain Research*, *243*, 220–230.

Luna, F. G., Aguirre, M. J., Martín-Arévalo, E., Ibáñez, A., Lupiáñez, J., & Barttfeld, P. (2023). Event-related potentials associated with attentional networks evidence changes in executive and arousal vigilance. *Psychophysiology*, *60*(8), e14272. https://doi.org/10.1111/psyp.14272

Maciejewska, K., & Froelich, W. (2021). Hierarchical classification of event-related potentials for the recognition of gender differences in the attention task. *Entropy*, *23*(11), 1547.

Mackintosh, N. J. (1998). REPLY TO LYNN. *Journal of Biosocial Science*, *30*(4), 533–539. https://doi.org/10.1017/S0021932098005331

MacLeod, J. W., Lawrence, M. A., McConnell, M. M., Eskes, G. A., Klein, R. M., & Shore, D. I. (2010). Appraising the ANT: Psychometric and theoretical considerations of the Attention Network Test. *Neuropsychology*, *24*(5), 637.

Mannarelli, D., Pauletti, C., Grippo, A., Amantini, A., Augugliaro, V., Currà, A., Missori, P., Locuratolo, N., De Lucia, M. C., Rinalduzzi, S., & Fattapposta, F. (2015). The Role of the Right Dorsolateral Prefrontal Cortex in Phasic Alertness: Evidence from a Contingent Negative Variation and Repetitive Transcranial Magnetic Stimulation Study. *Neural Plasticity*, *2015*, 410785. https://doi.org/10.1155/2015/410785

Martin, T. A., Keating, J. G., Goodkin, H. P., Bastian, A. J., & Thach, W. T. (1996). Throwing while looking through prisms: II. Specificity and storage of multiple gaze—throw calibrations. *Brain*, *119*(4), 1199–1211.

Martín-Arévalo, E., Laube, I., Koun, E., Farnè, A., Reilly, K. T., & Pisella, L. (2016). Prism adaptation alters electrophysiological markers of attentional processes in the healthy brain. *Journal of Neuroscience*, *36*(3), 1019–1030.

Mesulam, M. (1990). Large-scale neurocognitive networks and distributed processing for attention, language, and memory. *Annals of Neurology*, *28*(5), 597–613. https://doi.org/10.1002/ana.410280502

Michel, C., Pisella, L., Halligan, P. W., Luauté, J., Rode, G., Boisson, D., & Rossetti, Y. (2003). Simulating unilateral neglect in normals using prism adaptation: Implications for theory. *Neuropsychologia*, *41*(1), 25–39.

NAITO, Y., KOSHINO, Y., OTA, H., PIANO, M., WATANABE, A., INAGAKI, Y., TOKIKUNI, Y., & SAWAMURA, D. (2025). SHORT-TERM EFFECT OF PRISM ADAPTATION TREATMENT ON SEVERITY OF UNILATERAL SPATIAL NEGLECT FOLLOWING RIGHT HEMISPHERIC STROKE: A SYSTEMATIC REVIEW AND META-ANALYSIS. *Journal of Rehabilitation Medicine*, *57*, 42542. https://doi.org/10.2340/jrm.v57.42542

Nee, D. E., & D'Esposito, M. (n.d.). The hierarchical organization of the lateral prefrontal cortex. *eLife*, *5*, e12112. https://doi.org/10.7554/eLife.12112

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113.

Pélisson, D., Goffart, L., Guillaume, A., & Quinet, J. (2003). Visuo-motor deficits induced by fastigial nucleus inactivation. *The Cerebellum*, *2*(1), 71–76.

Petersen, S. E., & Posner, M. I. (2012). The Attention System of the Human Brain: 20 Years After. *Annual Review of Neuroscience*, *35*(1), 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Pisella, L., Michel, C., Gr**?**a, H., Tilikete, C., Vighetto, A., & Rossetti, Y. (2004). Preserved prism adaptation in bilateral optic ataxia: Strategic versus adaptive reaction to prisms. *Experimental Brain Research*, *156*(4), 399–408. https://doi.org/10.1007/s00221-003-1746-4

Pisella, L., Rode, G., Farnè, A., Tilikete, C., & Rossetti, Y. (2006). 21. Prism adaptation in the rehabilitation of patients with visuo-spatial cognitive disorders. *Current Opinion in Neurology*, *19*(6), 534–542. https://doi.org/10.1097/WCO.0b013e328010924b

Posner, M. I., & DiGirolamo, G. J. (1998). *Executive attention: Conflict, target detection, and cognitive control.* https://psycnet.apa.org/record/1998-07668-017

Posner, M. I., & Rothbart, M. K. (2007). Research on Attention Networks as a Model for the Integration of Psychological Science. *Annual Review of Psychology*, *58*(1), 1–23. https://doi.org/10.1146/annurev.psych.58.110405.085516

Pu, W., Luo, Q., Palaniyappan, L., Xue, Z., Yao, S., Feng, J., & Liu, Z. (2016). Failed cooperative, but not competitive, interaction between large-scale brain networks impairs working memory in schizophrenia. *Psychological Medicine*, *46*(6), 1211–1224.

Pulopulos, M. M., De Witte, S., Vanderhasselt, M.-A., De Raedt, R., Schiettecatte, J., Anckaert, E., Salvador, A., & Baeken, C. (2019). The influence of personality on the effect of iTBS after being stressed on cortisol secretion. *PLOS ONE*, *14*(10), e0223927. https://doi.org/10.1371/journal.pone.0223927

Raven, J. (2000). The Raven's Progressive Matrices: Change and Stability over Culture and Time. *Cognitive Psychology*, *41*(1), 1–48. https://doi.org/10.1006/cogp.1999.0735

Redding, G. M. (1978). Additivity in adaptation to optical tilt. *Journal of Experimental Psychology: Human Perception and Performance*, *4*(1), 178.

Redding, G. M. (2001). *On the sufficiency of object identity: Commentary.* https://psycnet.apa.org/record/2001-11673-011

Redding, G. M., Rossetti, Y., & Wallace, B. (2005a). Applications of prism adaptation: A tutorial in theory and method. *Neuroscience & Biobehavioral Reviews*, *29*(3), 431–444.

Redding, G. M., Rossetti, Y., & Wallace, B. (2005b). Applications of prism adaptation: A tutorial in theory and method. *Neuroscience & Biobehavioral Reviews*, *29*(3), 431–444.

Redding, G. M., & Wallace, B. (1990). Effects on Prism Adaptation of Duration and Timing of Visual Feedback During Pointing. *Journal of Motor Behavior*, *22*(2), 209–224. https://doi.org/10.1080/00222895.1990.10735511

Redding, G. M., & Wallace, B. (1992). Effects of Pointing Rate and Availability of Visual Feedback on Visual and Proprioceptive Components of Prism Adaptation. *Journal of Motor Behavior*, *24*(3), 226–237. https://doi.org/10.1080/00222895.1992.9941618

Redding, G. M., & Wallace, B. (1993). Adaptive Coordination and Alignment of Eye and Hand. *Journal of Motor Behavior*, *25*(2), 75–88. https://doi.org/10.1080/00222895.1993.9941642

Redding, G. M., & Wallace, B. (1994). Effects of Movement Duration and Visual Feedback on Visual and Proprioceptive Components of Prism Adaptation. *Journal of Motor Behavior*, *26*(3), 257–266. https://doi.org/10.1080/00222895.1994.9941681

Redding, G. M., & Wallace, B. (1996). Adaptive spatial alignment and strategic perceptual-motor control. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(2), 379.

Redding, G. M., & Wallace, B. (1997). Prism Adaptation During Target Pointing From Visible and Nonvisible Starting Locations. *Journal of Motor Behavior*, *29*(2), 119–130. https://doi.org/10.1080/00222899709600827

Redding, G. M., & Wallace, B. (2002). Strategie Calibration and Spatial Alignment: A Model From Prism Adaptation. *Journal of Motor Behavior*, *34*(2), 126–138. https://doi.org/10.1080/00222890209601935

Redding, G. M., & Wallace, B. (2003). First-trial adaptation to prism exposure. *Journal of Motor Behavior*, *35*(3), 229–245. https://doi.org/10.1080/00222890309602137

Redding, G. M., & Wallace, B. (2004). First-Trial "Adaptation" to Prism Exposure: Artifact of Visual Capture. *Journal of Motor Behavior*, *36*(3), 291–304. https://doi.org/10.3200/JMBR.36.3.291-304

Riley, E., Okabe, H., Germine, L., Wilmer, J., Esterman, M., & DeGutis, J. (2016). Gender differences in sustained attentional control relate to gender inequality across countries. *PloS One*, *11*(11), e0165100.

Robbins, T. W. (2000). Chemical neuromodulation of frontal-executive functions in humans and other animals. *Experimental Brain Research*, *133*(1), 130–138.

Rock, I., Goldberg, J., & Mack, A. (1966). Immediate correction and adaptation based on viewing a prismatically displaced scene. *Perception & Psychophysics*, *1*(10), 351–354. https://doi.org/10.3758/BF03215803

Ross, J. A., & Van Bockstaele, E. J. (2021). The Locus Coeruleus- Norepinephrine System in Stress and Arousal: Unraveling Historical, Current, and Future Perspectives. *Frontiers in Psychiatry*, *11*, 601519. https://doi.org/10.3389/fpsyt.2020.601519

Rossetti, Y., Koga, K., & Mano, T. (1993a). Prismatic displacement of vision induces transient changes in the timing of eye-hand coordination. *Perception & Psychophysics*, *54*(3), 355–364. https://doi.org/10.3758/BF03205270

Rossetti, Y., Koga, K., & Mano, T. (1993b). Prismatic displacement of vision induces transient changes in the timing of eye-hand coordination. *Perception & Psychophysics*, *54*(3), 355–364. https://doi.org/10.3758/BF03205270

Rubia, K., Hyde, Z., Halari, R., Giampietro, V., & Smith, A. (2010). Effects of age and sex on developmental neural networks of visual–spatial attention allocation. *Neuroimage*, *51*(2), 817–827.

Sarter, M., Givens, B., & Bruno, J. P. (2001). The cognitive neuroscience of sustained attention: Where top-down meets bottom-up. *Brain Research Reviews*, *35*(2), 146–160.

Schaie, K. W. (1994). The course of adult intellectual development. *American Psychologist*, *49*(4), 304.

Shaqiri, A., Roinishvili, M., Grzeczkowski, L., Chkonia, E., Pilz, K., Mohr, C., Brand, A., Kunchulia, M., & Herzog, M. H. (2018). Sex-related differences in vision are heterogeneous. *Scientific Reports*, *8*(1), 7521.

Spence, C., Nicholls, M. E. R., Gillespie, N., & Driver, J. (1998). Cross-modal links in exogenous covert spatial orienting between touch, audition, and vision. *Perception & Psychophysics*, *60*(4), 544–557. https://doi.org/10.3758/BF03206045

Spinnler, H. (1987). Standardizzazione e taratura italiana dei test neuropsicologici. *Italy J Neurol Sci*, *6*, 8–20.

Stoet, G. (2017). Sex differences in the Simon task help to interpret sex differences in selective attention. *Psychological Research*, *81*(3), 571–581. https://doi.org/10.1007/s00426-016-0763-4

Stratton, G. M. (1896). Some preliminary experiments on vision without inversion of the retinal image. *Psychological Review*, *3*(6), 611.

Sturm, W., De Simone, A., Krause, B. J., Specht, K., Hesselmann, V., Radermacher, I., Herzog, H., Tellmann, L., Müller-Gärtner, H.-W., & Willmes, K. (1999). Functional anatomy of intrinsic

alertness: Evidencefor a fronto-parietal-thalamic-brainstem network in theright hemisphere. *Neuropsychologia*, *37*(7), 797–805.

Sturm, W., & Willmes, K. (2001). On the Functional Neuroanatomy of Intrinsic and Phasic Alertness. *NeuroImage*, *14*(1), S76–S84. https://doi.org/10.1006/nimg.2001.0839

Surmeier, D. J. (2007). Dopamine and working memory mechanisms in prefrontal cortex. *The Journal of Physiology*, *581*(Pt 3), 885. https://doi.org/10.1113/jphysiol.2007.134502

Sylvester, C.-Y. C., Wager, T. D., Lacey, S. C., Hernandez, L., Nichols, T. E., Smith, E. E., & Jonides, J. (2003). Switching attention and resolving interference: fMRI measures of executive functions. *Neuropsychologia*, *41*(3), 357–370.

Taylor, J. A., & Thoroughman, K. A. (2008). Motor adaptation scaled by the difficulty of a secondary cognitive task. *PLoS One*, *3*(6), e2485.

Templeton, W. B., Howard, I. P., & Wilkinson, D. A. (1974). Additivity of components of prismatic adaptation. *Perception & Psychophysics*, *15*(2), 249–257. https://doi.org/10.3758/BF03213941

Thiel, C. M., Zilles, K., & Fink, G. R. (2005). Nicotine Modulates Reorienting of Visuospatial Attention and Neural Activity in Human Parietal Cortex. *Neuropsychopharmacology*, *30*(4), 810–820. https://doi.org/10.1038/sj.npp.1300633

Uhlarik, J. J., & Canon, L. K. (1971). Influence of concurrent and terminal exposure conditions on the nature of perceptual adaptation. *Journal of Experimental Psychology*, *91*(2), 233.

Urbanek, C., Neuhaus, A. H. M., Opgen-Rhein, C., Strathmann, S., Wieseke, N., Schaub, R., Hahn, E., & Dettling, M. (2009). Attention network test (ANT) reveals gender-specific alterations of executive function in schizophrenia. *Psychiatry Research*, *168*(2), 102–109.

Urbanek, C., Weinges-Evers, N., Bellmann-Strobl, J., Bock, M., Dörr, J., Hahn, E., Neuhaus, A. H., Opgen-Rhein, C., Ta, T. M. T., Herges, K., Pfueller, C. F., Radbruch, H., Wernecke, K. D., Ohlraun, S., Zipp, F., Dettling, M., & Paul, F. (2010). Attention Network Test reveals alerting network dysfunction in multiple sclerosis. *Multiple Sclerosis (Houndmills, Basingstoke, England)*, *16*(1), 93–99. https://doi.org/10.1177/1352458509350308

Vossel, S., Bauer, M., Mathys, C., Adams, R. A., Dolan, R. J., Stephan, K. E., & Friston, K. J. (2014). Cholinergic Stimulation Enhances Bayesian Belief Updating in the Deployment of Spatial Attention. *Journal of Neuroscience*, *34*(47), 15735–15742. https://doi.org/10.1523/JNEUROSCI.0091-14.2014

Wager, T. D., Jonides, J., & Reading, S. (2004a). Neuroimaging studies of shifting attention: A meta-analysis. *Neuroimage*, *22*(4), 1679–1693.

Wager, T. D., Jonides, J., & Reading, S. (2004b). Neuroimaging studies of shifting attention: A meta-analysis. *Neuroimage*, *22*(4), 1679–1693.

Wallace, B., Melamed, L. E., & Cohen, R. R. (1973). An analysis of aftereffects in the measurement of the correction effect. *Perception & Psychophysics*, *14*(1), 21–23. https://doi.org/10.3758/BF03198610

Weiner, M. J., Hallett, M., & Funkenstein, H. H. (1983). Adaptation to lateral displacement of vision in patients with lesions of the central nervous system. *Neurology*, *33*(6), 766–766. https://doi.org/10.1212/WNL.33.6.766

Weiss, E., Siedentopf, C. M., Hofer, A., Deisenhammer, E. A., Hoptman, M. J., Kremser, C., Golaszewski, S., Felber, S., Fleischhacker, W. W., & Delazer, M. (2003). Sex differences in brain activation pattern during a visuospatial cognitive task: A functional magnetic resonance imaging study in healthy volunteers. *Neuroscience Letters*, *344*(3), 169–172.

Welch, R. B. (2013). *Perceptual modification: Adapting to altered sensory environments*. Elsevier. https://books.google.com/books?hl=en&lr=&id=9RglBQAAQBAJ&oi=fnd&pg=PP1&dq=Welch,+R.B.,+1978.+Perceptual+Modification:+Adapting+to+Altered+Sensory+Environments.+Academic+Press,+New+York.&ots=0bfANc1C6G&sig=Do71Tsmdomq9mDGgVgQdzpYpTRo

Welch, R. B., & Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin*, *88*(3), 638.

Witte, E. A., Davidson, M. C., & Marrocco, R. T. (1997). Effects of altering brain cholinergic activity on covert orienting of attention: Comparison of monkey and human performance. *Psychopharmacology*, *132*(4), 324–334.

Xiao, M., Ge, H., Khundrakpam, B. S., Xu, J., Bezgin, G., Leng, Y., Zhao, L., Tang, Y., Ge, X., Jeon, S., Xu, W., Evans, A. C., & Liu, S. (2016). Attention Performance Measured by Attention Network Test Is Correlated with Global and Regional Efficiency of Structural Brain Networks. *Frontiers in Behavioral Neuroscience*, *10*, 194. https://doi.org/10.3389/fnbeh.2016.00194