Investigating Implicit And Explicit Contributions To Dual Visuomotor Adaptation

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Statement of Contributions

I hereby declare that I am the sole author of this Master of Science thesis. My contributions to this thesis include: a literature review, participant recruitment and data collections, analysis and compilation of data, statistical analysis, and the writing of this thesis in its entirety. All of the aforementioned actions were performed under the guidance and mentorship of Dr. Erin K. Cressman, my research supervisor.

The original experimental design was revised in collaboration with Dr. Erin Cressman, taking into account the recommendations and ideas of my thesis advisory committee: Dr. Anthony Carlsen and Dr. Michael Carter. Dr. Cressman provided all editorial feedback and is co-author of the article presented in this thesis.

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Abstract

The ability to seamlessly switch between different visuomotor mappings is critical for effective interactions in a dynamic environment. This experiment aimed to establish the implicit (unconscious) and explicit (conscious strategy) contributions to adapting one's reaches to two small visuomotor mappings simultaneously (dual visuomotor adaptation). 59 right-handed participants were divided into two groups: a Dual adaptation group and a Single adaptation group. The Dual group trained to reach when cursor feedback was rotated (i) 20° clockwise (CW) relative to hand motion when a target was displayed in the left visual workspace and (ii) 20° counterclockwise (CCW) relative to hand motion when a target was displayed in the right visual workspace. The Single group trained to reach with just one 20° cursor distortion (CW or CCW) regardless of visual workspace. Results revealed that while all participants adapted their reaches to the distorted cursor feedback, those who reached with a Single CCW cursor distortion demonstrated significantly greater visuomotor adaptation in comparison to those who reached with a Single CW cursor distortion or with two opposing cursor distortions (Dual group). For all groups, visuomotor adaptation arose implicitly. However, the Dual group demonstrated significantly less implicit adaptation than participants who trained with a Single CW distortion even after additional reach training trials. Together, these results indicate a role for implicit processes in simultaneously updating one's reaches to two small visuomotor mappings.

Chapter I: Literature Review

The goal of this research is to better understand the contributions of implicit and explicit processes to dual visuomotor adaptation. To situate this research within the context of current findings, this review of literature will first provide an overview of visuomotor adaptation. We will then outline previous research examining dual visuomotor adaptation, including the possibility of learning one visuomotor mapping interfering with the learning of a second visuomotor mapping. This will be followed by a discussion of the mechanisms underlying visuomotor adaptation, highlighting implicit and explicit contributions and their potential contribution to dual visuomotor adaptation. Finally, the literature review will conclude with the research question and expected outcomes.

Visuomotor adaptation

Every day we perform a variety of motor tasks, such as reaching, walking, balancing, and moving our eyes. These actions enable us to manipulate tools and interact with our ever changing environment (Bastian, 2008). A change in visuomotor mapping is experienced when one goes from interacting directly with visual objects to having to move a mouse to navigate around a computer monitor. For instance, sliding a computer mouse forward moves the cursor upwards on the screen, creating a 90° difference between the directions of hand and cursor motion. Most of us can manipulate the mouse in an 'automatic' manner, without engaging conscious strategies to achieve a target (i.e., move the mouse to an icon we want to click on). However, if we are to suddenly switch and use a friend's computer, with different mouse settings, we may find that our movements are initially inaccurate. This movement inaccuracy can be resolved thought the process of motor adaptation (Bastian, 2008; Krakauer et al., 2019; Krakauer, 2009)

Motor adaptation is a form of motor learning that leads to a reduction in movement errors over trials, when errors arise due to a systematic perturbation in the environment (Bastian, 2008;

Krakauer, 2009). According to Bastian (2008) there are three criteria that must be met for motor adaptation to occur: (1) the movement is a specific action that only requires changes based on changes in the environment (e.g., change of cursor direction); (2) movement adaptation occurs over time with practice and repetitive movements, which may take minutes to hours; (3) when movements are adapted, individuals will demonstrate aftereffects (i.e., erroneous movements in the opposite direction of the motor distortion), such that these movements must then be de-adapted with practice. A common form of motor adaptation studied in the laboratory is visuomotor adaptation. Visuomotor adaptation studies manipulate the visual representation of the target and/or the reaching limb, which creates a conflict between the visual and proprioceptive representations of one's hand position in space (Cressman & Henriques, 2009; Krakauer, 2009).

Early studies examining visuomotor adaptation manipulated visual information by having participants wear prism goggles that laterally displaced the reaching environment and reaching limb in the leftward or rightward direction (Fernández-Ruiz & Díaz, 1999; Held, 1965). Visuomotor adaptation can also be examined by having participants reach in virtual reality environments, where the cursor on the screen misrepresents the position of their hand in space (Cressman & Henriques, 2009; Heuer & Hegele, 2008; Krakauer et al., 2000). For example, the cursor motion could be rotated clockwise (CW; or counterclockwise (CCW)) relative to one's actual hand motion (e.g., by 20°). When first reaching with the visuomotor distortion, participants typically experience an error, such that the cursor lands to the right of the target. However, movements are adapted over trials, such that participants aim to the left of the target, so that the cursor once again lands on the target as desired (Cressman & Henriques, 2010, 2009; Heuer & Hegele, 2008; Wang & Lei, 2015).

Visuomotor adaptation in virtual environments has been proposed to arise in part due to an unconscious (i.e., implicit) updating of the internal model in response to a sensory prediction error signal (Lee et al., 2018; Wolpert et al., 1995). The internal model is a neural mechanism that consists of the forward model and the inverse model (Kawato, 1999; Lee et al., 2018; Wolpert et al., 1995). The forward model predicts the sensory consequences of the movement based on the motor command produced (i.e., the inverse model; Kawato, 1999). When reaching with a visuomotor distortion, the predicted and actual sensory feedback do not match, creating a sensory prediction error. This sensory discrepancy between the seen position of the cursor and predicted position of the hand leads to updating of the inverse model and associated forward model (Lee et al., 2018; Wolpert et al., 1995).

Dual visuomotor adaptation

Typically, visuomotor adaptation studies examine one's ability to update a single internal model under varying practice conditions (e.g., changes in the magnitude of the cursor rotation (Salomonczyk et al., 2011), availability of cursor feedback (Cressman & Henriques, 2009; Franklin et al., 2014), instructions provided (Lee et al., 2018; Mazzoni & Krakauer, 2006), etc.). While results are informative, they do not speak to one's ability to adapt to two visuomotor mappings (i.e., update two internal models) simultaneously. The ability to activate and switch between different visuomotor mappings is critical, as it allows us to perform two or more tasks in series of one another (e.g., using your computer mouse to browse the internet and then grabbing your cup of coffee to drink), or to switch between similar tasks (i.e., browsing the internet on your computer and then writing notes by hand). Our ability to complete multiple motor tasks in series or switch between motor tasks is a necessity as we proceed with daily activities.

In a typical dual visuomotor adaptation paradigm, participants look to simultaneously adapt to two opposing visuomotor distortions (i.e., a CW and CCW cursor rotation are presented on alternate trials; Ayala et al., 2015; Hegele & Heuer, 2010; Hinder et al., 2007; Woolley et al., 2007). To date, dual visuomotor adaptation has been found to be contingent on the sensory cues that are presented to signal the direction of a given cursor rotation. For example, task-irrelevant cues that provide information extrinsic to the reaching movement have lead to inconclusive results with respect to facilitating dual visuomotor adaptation (Baldeo & Henriques, 2013; Hegele & Heuer, 2013; Osu et al., 2004; Woolley et al., 2007). Examples of task irrelevant cues include changing the target or background colour to signal different visuomotor rotations (Forano et al., 2021; Osu et al., 2004; Woolley et al., 2007).

In 2007, Woolley and colleagues looked to assess the influence of colour cues on dual visuomotor adaptation. Targets were displayed and the different rotations cued by either a red (CW) or blue (CCW) background colour. Results indicated that participants did not demonstrate significant aftereffects when the different rotations were cued through background colour, suggesting that colour cues were not effective at facilitating dual visuomotor adaptation. Hinder and colleagues' (2008) work also demonstrated a lack of dual visuomotor adaptation when opposing rotations were cued through changes in background colour.

In contrast to the colour cues mentioned above, dual visuomotor adaptation has been shown to arise when task-relevant cues are presented during experimentation. Task relevant cues incorporate movement characteristics of physical presence in the natural environment, such as the visual workspace or target location (Schween et al., 2018). Task-relevant cues allow the sensorimotor system to identify and associate meaningful changes within the environment with appropriate motor commands for task succession (Schween et al., 2018). For example, Woolley

et. al. (2007) found that cueing the direction of the rotation by the location of target presentation in the left or right side of the visual workspace led to dual visuomotor adaptation as demonstrated by aftereffects (see Figure 1.1, see also Hegele & Heuer, 2013; Schween et al., 2018; Wang & Müsseler, 2014).

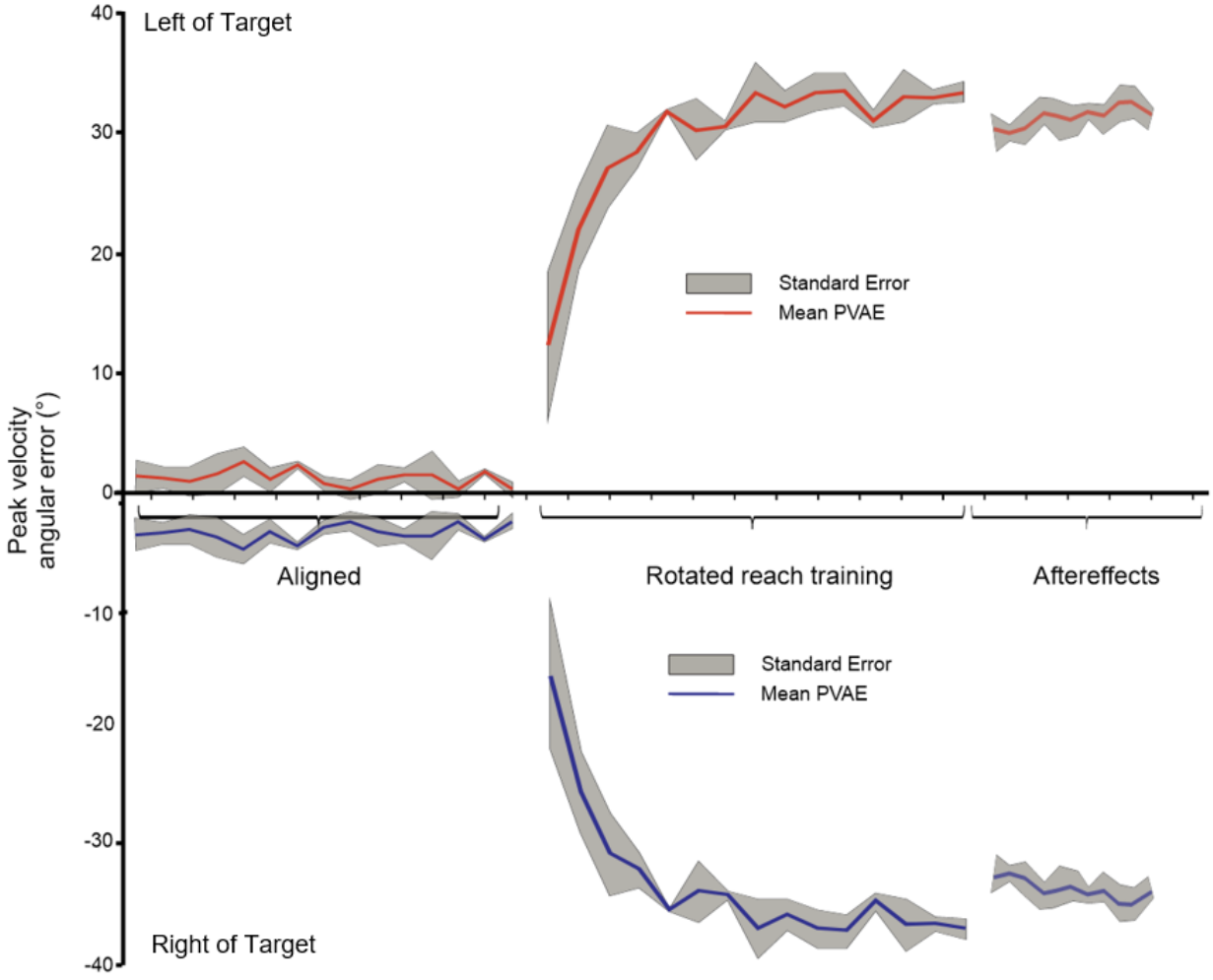


Figure 1.1. Typical reaching errors demonstrating dual visuomotor adaptation

Red curves represent typical errors when adapting to a 40° CW visuomotor distortion associated with reaching to a target in the left visual workspace and Blue curves represent typical errors when adapting to a 40° CCW visuomotor distortion associated with reaching to a target in the right visual workspace. The y-axis represents angular error at peak velocity, whereas the x-axis represents trials over time. Aligned trials demonstrate little to no error for both visual workspaces, whereas rotated trials demonstrate significant changes in reaches in the opposite direction of the imposed visuomotor distortion. Aftereffect trials are completed in the absence of cursor feedback and demonstrate that visuomotor adaptation has occurred.

Within this cue manipulation, participants reach from the same physical start position, in the middle of the workspace, on every trial. However, participants see a home position and target on either the left or the right side of the visual workspace, where the left workspace may be associated with a CW rotation, and the right workspace associated with a CCW rotation (see Figure 1.2).

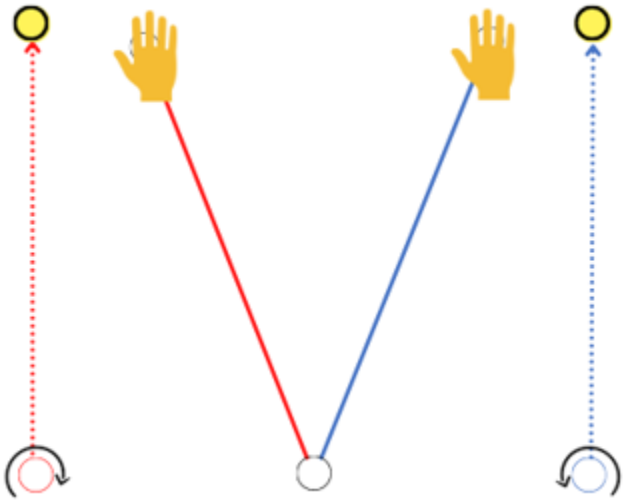


Figure 1.2. Experimental set up to examine dual adaptation

The blue dotted line denotes cursor motion when the visual home position is displayed in the right visual workspace, and the solid blue line corresponds to the required hand path to counteract the CCW rotation. The red dotted line denotes cursor motion completed when the visual home position is displayed in the left visual workspace, and the solid red line corresponds to the required hand path to counteract the CW rotation.

Trials with targets presented in the left and right workspace are typically interleaved. These findings of dual visuomotor adaptation arising when the different rotations are cued by target location in a visual workspace have been replicated (see also Baldeo & Henriques, 2013; Forano et al., 2021; Hegele & Heuer, 2010; Schween et al., 2018; Wang & Müsseler, 2014; Woolley et al., 2007).

Dual visuomotor adaptation demonstrates the ability of our motor system to seamlessly switch between two visuomotor mappings. However, learning these two opposing visuomotor mappings in close succession could lead to interference if both tasks competed for the same neural resources. Inference is typically examined within an ABA interference paradigm, where participants will learn a single visuomotor mapping (e.g., task A = CW cursor rotation) prior to learning a secondary task (e.g., task B = CCW cursor rotation). Retrograde interference in visuomotor adaptation refers to the phenomenon where the learning of a subsequent task interferes with the memory of a previously learned visuomotor adaptation task. For example, Krakauer and colleagues (2005) found that when participants first learned a 30° CW rotation (task A) followed by learning a 30° CCW rotation (task B), participants experienced inference when reintroduced to task A, such that their reaching performance was similar to their initial learning of task A (i.e., there was no initial benefit of having learned task A previously). In contrast, anterograde interference in visuomotor adaptation refers to the phenomenon of where the learning of one task interferes with the learning of a subsequent task. For example, Lerner and colleagues (2020) found that when participants learned task B (30° CW rotation) following learning of task A (30° CCW rotation), participants demonstrated a bias towards reaching performance observed in task A. Specifically, participants initially reached right of the target, suggesting anterograde interference from task A to task B.

Previous dual visuomotor adaptation paradigms do not discuss their results with respect to interference per se. In contrast to the more traditional ABA experimental paradigms, dual visuomotor adaptation paradigms are designed with frequent switches between the two visuomotor mappings across trials. One assumes that interference would arise, especially early on when the two visuomotor mappings are introduced. However, dual adaptation has shown that it is possible to continuously switch between two visuomotor mappings, without a decline in performance after adaptation has arisen (Forano et al., 2021; Hegele & Heuer, 2010; Schween et al., 2018; Woolley et al., 2007).

Mechanisms underlying visuomotor adaptation

As mentioned above, visuomotor adaptation has been proposed to be driven implicitly as a result of experiencing a sensory-prediction error (Bond & Taylor, 2015; Neville & Cressman, 2018; Taylor et al., 2014). In addition to implicit processes, explicit processes (i.e., conscious strategy) have also been suggested to influence reaches when the visuomotor distortion is present. According to state-space models, implicit and explicit adaptation correspond to slow and fast neural processes respectively (McDougle et al., 2015). Explicit processes are suggested to arise due to experiencing a target error (i.e., the cursor does not land on the target), and their engagement is dependent on the size of the visuomotor distortion introduced (Modchalingam et al., 2019; Neville & Cressman, 2018) and instructions provided (Benson et al., 2011; Mazzoni & Krakauer, 2006; Neville & Cressman, 2018; Taylor et al., 2014). For example, adaptation to a cursor rotation of 40° or more has been shown to be largely explicit in nature (see Neville & Cressman, 2018; Werner et al., 2015). These explicit contributions lead to rapid changes in reaching when a large (i.e., 40° or greater) cursor rotation is introduced, especially when instructions on how to counteract the visuomotor rotation are provided (Mazzoni & Krakauer, 2006; Neville & Cressman, 2018) .

Implicit and explicit adaptation are proposed to arise due to different error signals, and hence be independent processes (Bond & Taylor, 2015; Mazzoni & Krakauer, 2006; Neville & Cressman, 2018; Taylor et al., 2014; Werner et al., 2015). In accordance with this proposal, Mazzoni and Krakauer's (2006) found evidence of implicit adaptation even when participants did not experience any target error. In their study, participants were presented with a display of 8 visual landmarks, spaced 45° apart around the circumference of a circle. Participants were informed about the 45° CCW rotation and were instructed to counteract the visuomotor distortion by aiming to the neighbouring visual landmark in the CW direction. Mazzoni and Krakauer (2006) found that while the use of this reaching strategy initially resulted in improved performance, as trials continued, reaching errors increased. Specifically, participants began to adapt their reaches implicitly in response to the sensory discrepancy between their aiming direction and resulting sensory feedback. While there has been much investigation into the contribution of implicit and explicit processes underlying visuomotor adaptation, limited work has looked at how these processes contribute to dual visuomotor adaptation.

Implicit and explicit contributions to dual visuomotor adaptation

Previous work has alluded to the possibility that explicit processes are responsible for dual visuomotor adaptation, with Hinder and colleagues (2008) first suggesting that explicit processes underlie dual visuomotor adaptation. Implicit and explicit contributions to dual visuomotor adaptation were then directly investigated by Hegele and Heuer (2010) in young and older adults. In their paradigm, opposing 75° visuomotor rotations were cued through a visual separation of the targets in the workspace. Implicit adaptation was assessed through aftereffects in no-cursor reaches, while explicit adaptation was assessed by requiring participants to verbally instruct the researcher on how to adjust an orientation line so that it matched the direction of where the hand would be required to move to get the cursor to the target. Results indicated that

dual visuomotor adaptation was only present in young adults and that this adaptation was driven explicitly. Schween and colleagues (2018) used similar methods when assessing implicit and explicit contributions to dual visuomotor adaptation at trained and novel targets after participants reached with opposing 75° visuomotor rotations. Using these methods, Schween and colleagues (2018) found dual visuomotor adaptation was largely driven by explicit processes to all target locations.

In contrast to the (explicit) line orientation task described above and imposing a large cursor rotation, Ayala and Henriques (2021) used the Process Dissociation Procedure (PDP) to assess implicit and explicit contributions to dual visuomotor adaptation in response to small cursor rotations of 30°. The PDP was originally put forth by Jacoby (1991) in the field of cognitive psychology as a tool to measure how automatic and intentional memory contribute to recognition. Werner and colleagues (2015) then modified the PDP to examine the contributions of implicit and explicit processes to visuomotor adaptation. Within their PDP framework, participants are asked to either use (inclusion trials) or withhold from using (exclusion trials) any strategy they have learned when reaching in the absence of cursor feedback, with the assumption that conscious knowledge is controllable. Implicit adaptation is determined by reaching errors on exclusion trials relative to the target, while explicit adaptation is established by computing the difference in reaching errors between inclusion and exclusion trials (Heirani Moghaddam et al., 2021; Modchalingam et al., 2019; Neville & Cressman, 2018; Werner et al., 2015).

In Ayala and Henriques (2021), participants reached to a target while they saw target boxes (left or right of the target) that indicated the direction of the 30° visuomotor distortion on that trial (left target box = CW rotation and right target box = CCW rotation). All trials were completed within the same visual workspace. Ayala and Henriques (2021) found no evidence of

dual visuomotor adaptation arising when participants reached with the cursor present. Furthermore, when examining the no-cursor PDP trials, reaching errors did not differ from baseline, demonstrating a lack of implicit and explicit adaptation. Given the lack of dual visuomotor adaptation observed, these findings do not allow us to draw conclusions regarding the processes underlying dual visuomotor adaptation to small cursor distortions.

Just recently, Bernier and colleagues (2023) established that implicit processes can contribute to dual visuomotor adaptation to small cursor rotations. In their study, participants adapted their reaches to separate targets which were associated with either a 5° CW or CCW cursor rotation or aligned cursor feedback. Based on performance during aftereffect trials and a post-assessment question, they concluded that participants were not aware of changes in their reaches to targets associated with rotated cursor feedback and hence dual visuomotor adaptation arose implicitly. However, this study did not directly assess explicit adaptation and implicit adaptation was established in the presence of aligned cursor feedback (i.e., did not use the PDP as done by Ayala & Henriques, 2021).

From this limited work, it appears that explicit processes are primarily responsible for dual visuomotor adaptation in response to large cursor distortions, although, implicit processes may contribute when small cursor rotations are introduced. As indicated previously, large cursor rotations typically lead to participants becoming aware of the cursor distortion and strategically altering their reaches (see Mechanisms underlying visuomotor adaptation). Thus, it is perhaps not surprising that explicit processes have been primarily responsible for the dual visuomotor adaptation previously observed (Hegele & Heuer, 2010, 2013; Schween et al., 2018; Woolley et al., 2007). It is unclear if explicit processes also underlie dual visuomotor adaptation to small cursor rotations (e.g., 30° or less), as previous work utilizing smaller rotation sizes has not

evoked dual visuomotor adaptation (see Ayala & Henriques, 2021) or not assessed explicit adaptation (see Bernier et al, 2023). Thus, the processes driving dual visuomotor adaptation to small cursor rotations remain unclear.

Purpose and Research Question

As outlined above, dual visuomotor adaptation is typically studied in the laboratory by having participants reach with two opposing visuomotor rotations. It has been demonstrated that dual visuomotor adaptation arises when participants are introduced to the opposing rotations using task-relevant cues, such as visually separating target locations in the workspace (Forano et al., 2021; Hegele & Heuer, 2010; Schween et al., 2018; Woolley et al., 2007). The goals of the current research were to (1) establish implicit (i.e., unconscious) and explicit (i.e., conscious strategy) contributions underlying dual visuomotor adaptation when adapting to opposing small 20° cursor rotations and (2) determine if the engagement of implicit and explicit processes differ between dual visuomotor adaptation and adaptation to a single 20° visuomotor rotation.

Similar to the work by Hegele and Heuer (2010) and Schween and colleagues (2018), participants completed a dual visuomotor adaptation paradigm in which they looked to adapt their reaches to two opposing 20° visuomotor rotations that were cued through target presentation on the left and right side of the workspace (Dual group of participants). Control participants reached with a single 20° cursor rotation (Single; CW or CCW), while seeing similar target presentations as the Dual group. Using the PDP, implicit and explicit contributions to visuomotor adaptation were assessed for all participants.

It has been suggested that dual visuomotor adaptation arises primarily through explicit processes (see Forano et al., 2021; Hegele & Heuer, 2010; Osu et al., 2004; Schween et al., 2018; Woolley et al., 2007). However, the processes underlying dual visuomotor adaptation to small

visuomotor rotations are unknown. We hypothesized that implicit processes would underlie both dual and single visuomotor adaptation when adapting one's reaches to small cursor rotations. We also hypothesized that the extent of implicit contributions would be similar between the Dual and Single visuomotor adaptation groups when adapting to small cursor rotations. Together, these results would suggest that implicit processes can contribute to dual visuomotor adaptation, adding clarification to their role within dual visuomotor adaptation and allowing us to make comparisons to the traditional single visuomotor adaptation paradigm.

Chapter II: Research Article

Introduction

Our ability to seamlessly switch between different visuomotor mappings is critical to interacting effectively in an ever-changing environment. For example, this ability allows us to switch between using a mouse to browse the internet on our computer and reaching directly towards a cup of coffee. It is possible to study one's ability to switch between different visuomotor mappings in a laboratory setting by using a dual visuomotor adaptation paradigm. A dual visuomotor adaptation paradigm typically introduces two opposing visuomotor distortions, such that the direction of cursor motion on the screen randomly switches between being rotated clockwise (CW) and counterclockwise (CCW) relative to hand motion across trials (Hegele & Heuer, 2010; Heuer & Hegele, 2008; Woolley et al., 2007).

To date, much research has looked at examining the processes underlying visuomotor adaptation to a single visuomotor distortion (Baraduc & Wolpert, 2002; Bastian, 2008; Ghahramani et al., 1996; Magescas & Prablanc, 2006; Simani et al., 2007; Vetter et al., 1999). Within a single visuomotor distortion paradigm, the cursor motion could be rotated 20º CW (or CCW) relative to hand motion. In this case, participants mis-reach when the cursor rotation is first introduced, such that the cursor does not land on the target (Franklin et al., 2014; Neville & Cressman, 2018; Salomonczyk et al., 2011; Werner et al., 2015). With continued reaching trials, participants gradually adjust their motor commands to compensate for the visuomotor distortion, aiming to the left of the target so that the cursor once again lands on the target as required. These changes in motor commands persist after the cursor distortion is removed, such that participants continue to aim to the left of the target demonstrating aftereffects (Baraduc & Wolpert, 2002; Buch et al., 2003; Cressman & Henriques, 2009; Simani et al., 2007).

Aftereffects are proposed to reflect implicit adaptation, arising in the absence of conscious awareness as a result of experiencing a sensory-prediction error (Wolpert et al., 1998). The sensory-prediction error arises when reaching with a visuomotor distortion, as the predicted and actual sensory feedback do not match. This sensory discrepancy between the seen position of the cursor and predicted position of the hand leads to implicitly updating the inverse model (i.e., motor command) and associated forward model (i.e., expected sensory feedback; Lee et al., 2018; Wolpert et al., 1995). In contrast to implicit adaptation, explicit adaptation (i.e., conscious strategy) is suggested to arise when experiencing a target error (i.e., the cursor does not land on the target; Modchalingam et al., 2019; Neville & Cressman, 2018), and the engagement of explicit processes has been shown to be dependent on the size of the visuomotor distortion introduced (see Modchalingam et al., 2019; Neville & Cressman, 2018). Specifically, Neville and Cressman (2018) found that the extent of explicit adaptation increased across groups of participants who reached with increasing cursor distortion sizes (20°, 40°, or 60°), such that the greatest explicit adaptation was found for participants adapting to a 60° cursor rotation. In contrast, implicit adaptation did not increase in magnitude across the different groups, implying a limit to potential implicit adaptation (see also Taylor and colleagues, 2014). Moreover, when reaching with a 20° cursor rotation, results indicated that visuomotor adaptation was driven implicitly, with negligible explicit contributions, even when participants were provided with a reaching strategy on how to counteract the visuomotor distortion.

Neville and Cressman (2018) used the Process Dissociation Procedure (PDP) to establish implicit and explicit contributions when reaching with a single visuomotor distortion. Within the PDP framework, participants are asked to either use (inclusion trials) or withhold from using (exclusion trials) any strategy they have learned when reaching, with the assumption that

conscious knowledge is controllable (Werner et al., 2015). Exclusion trials are similar to typical aftereffect trials where participants are instructed to reach to a target with no-cursor feedback and are used to establish implicit adaptation. The difference in reaching errors between inclusion and exclusion trials is proposed to reflect explicit adaptation. Currently, the contributions of implicit and explicit processes to dual visuomotor adaptation remain unclear.

Previous research investigating the processes underlying dual visuomotor adaptation has tended to introduce large cursor rotations (e.g., 75°), and in turn, attributed dual visuomotor adaptation to explicit processes (Hegele & Heuer, 2010; Schween et al., 2018; Woolley et al., 2007). To date, we are aware of only two studies that have examined dual visuomotor adaptation to small cursor rotations. In Ayala and Henriques (2021), participants reached with small opposing cursor rotations of 30° and implicit and explicit contributions to dual visuomotor adaptation were assessed using the PDP. Unfortunately, their results suggested dual visuomotor adaptation did not arise when the rotated cursor feedback was presented, limiting their ability to draw conclusions from the PDP trials (Ayala and Henriques, 2021). Recently, Bernier and colleagues (2023) assessed implicit contributions to small opposing cursor perturbations. In their study, participants looked to concurrently adapt their reaches to separate targets, which were either associated with a 5° CW or CCW cursor rotation or aligned cursor feedback. Bernier and colleagues (2023) found that participants were able to fully compensate for the imposed cursor rotations at the designated targets in the absence of awareness. However, explicit (and implicit) contributions were not directly assessed. Thus, the contributions of implicit and explicit processes to dual visuomotor adaptation when reaching with two small cursor rotations are unclear.

The purpose of the present study was to establish implicit and explicit contributions underlying dual visuomotor adaptation to opposing small cursor rotations (i.e., 20°) and to determine if the engagement of implicit and explicit processes differ between dual visuomotor adaptation and adaptation to a single 20° cursor rotation. Two groups of participants were recruited such that one group reached with two opposing small visuomotor rotations (i.e., Dual group: reached with a 20° CW cursor rotation relative to hand motion when a target was presented in the left visual workspace and a 20° CCW cursor rotation relative to hand motion when a target was presented in the right visual workspace). The second group of participants adapted their reaches to a single cursor rotation (i.e., Single group: reached with either a 20° CW or a 20° CCW cursor rotation relative to hand motion regardless of whether the target was presented in the left or right visual workspace). The PDP was used to assess implicit and explicit contributions to visuomotor adaptation for all participants. We hypothesized that implicit processes would underlie both dual and single visuomotor adaptation when adapting reaches to small 20° cursor rotations. These results would suggest that implicit processes can contribute to dual visuomotor adaptation when reaching with small cursor rotations, adding clarification to the role of implicit processes within dual visuomotor adaptation and allowing us to make comparisons to the traditional single visuomotor adaptation paradigm.

Methods

Participants

A total of 59 right-handed participants (43 females, $\bar{x}$ = 20 years of age) were recruited from the University of Ottawa community to participate in this study to meet the required power. Specifically, to answer our first research question regarding if implicit processes can underlie dual visuomotor adaptation , an a-priori power analysis using G*Power with the following input parameters was conducted: a power of 0.8, effect size of 0.5 and Type 1 error (alpha) probability

of 0.05 (Cohen, 1992; Faul, Erdfelder, Lang & Buchner, 2007, Lakens, 2022), resulting in a required sample size of 27 participants in the Dual group. To note, the effect size was determined by taking into account the extent of implicit adaptation previously achieved when reaching with a 20° cursor rotation in a single visuomotor adaptation paradigm (see Neville & Cressman, 2018). Given that Neville and Cressman (2018) found a large effect, we conservatively lowered the effect size to a moderate effect of 0.5.

All participants were naïve to the purpose of the study and had not participated in a visuomotor adaptation study previously. Participants were healthy and had no history of any neurological, motor, or sensory impairment. Participants had normal or corrected-to-normal vision (i.e., prescription eyeglasses or contact lenses) and were all right-handed as established via the Edinburgh Handedness Questionnaire (M = 83.5, SD = 2.34 ; Oldfield, 1971). Participant recruitment and data collection commenced after ethical approval was attained from the University of Ottawa's Health Sciences and Science Research Ethics Board. Prior to starting the experiment, all participants provided written informed consent.

Apparatus

During testing, participants were seated in a height-adjustable chair directly in front of the experimental apparatus (KINARM End-Point Lab; KINARM, Kingston, ON; Figure 2.1). Participants positioned the chair such that their forehead comfortably rested against the headrest and they were able to reach to all targets within the designated workspace while grasping the robot handle with their dominant right hand. The position of the chair was maintained throughout the experimental session.

As shown in Figure 2.1, visual targets were displayed on a downward facing monitor, located 20.5 cm above a reflective surface, which was located 20.5 cm above the KINARM

handle. Thus, visual stimuli appeared to lie in the same horizontal plane as the right hand holding the handle. Vision of participants' right limb was occluded by the reflective surface and a black cloth draped across participants' shoulders which attached to the apparatus. Once participants stated they were comfortably seated, the lights in the room were turned off and testing began.

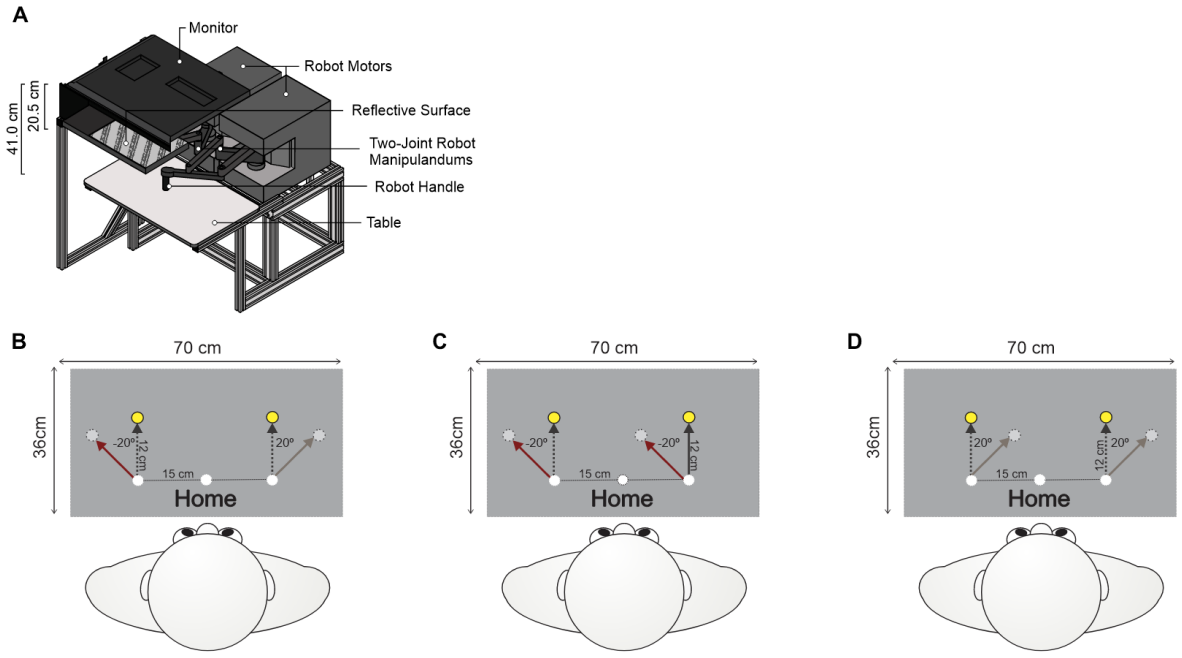


Figure 2.1. Experimental apparatus and experimental set-up for conditions

A) Side-view of the experimental KINARM End-Point Lab (KINARM, Kingston, ON). B) Top-view illustrating the visual workspace and cursor rotations experienced by the Dual adaptation group. The home position of the hand (illustrated by the white circle) was within the middle of the left and right visual workspaces. The two reach training targets (yellow circles) were located 12 cm directly above the left and right visual home positions (white circles). During rotated reach training trials, the cursor's trajectory was rotated 20° clockwise or counterclockwise, thus, requiring a 20° counterclockwise hand movement (garnet arrow, left visual workspace) or 20° clockwise hand movement (grey arrow, right visual workspace) to successfully have the cursor land on the target. The dotted black line demonstrates the cursor's movement trajectory to the target. C) Top-view illustrating the visual workspace and cursor rotation experienced by participants in the Single group who reached with a clockwise visuomotor rotation. During rotated reach training trials, the cursor's trajectory was rotated 20° clockwise relative to hand motion in both the left and right visual workspaces, requiring 20° counterclockwise hand

movements (garnet arrows). D) Top-view illustrating the visual workspace and cursor rotation experienced by participants in the Single group who reached with a counterclockwise visuomotor rotation. During rotated reach training trials, the cursor's trajectory was rotated 20° counterclockwise relative to hand motion in both the left and right visual workspaces, requiring 20° clockwise hand movements (grey arrows).

Experiment overview

General overview

Participants were randomly assigned to one of two groups, such that there were 30 participants in the Dual Adaptation (Dual) group and 29 participants in the Single Adaptation (Single) group. Within the Single group, 15 participants reached with a 20° CW rotation and 14 participants reached with a 20° CCW rotation. All groups saw the same visual home positions and targets; however, direction of the cursor rotation introduced was manipulated across groups.

Participants completed two testing phases (baseline and adaptation phases) and sets of reaches as outlined below. The baseline phase began with familiarization trials, enabling participants to reach to the targets while stimuli were presented within the left and right visual workspaces. Then, both groups completed reaches while seeing a cursor that was aligned with their hand motion with respect to movement direction (i.e., aligned reach training) to establish their baseline movement errors. In addition to reach training trials, participants also completed no-cursor reaches. The no-cursor reaches were performed to the same visual targets as reach training trials. For both groups, these trials were completed while seeing the left or right visual home position (i.e., 5 trials with the left and 5 trials with the right visual home position presented). The order in which the left or right visual home position was presented first was counterbalanced across participants. The second adaptation phase consisted of rotated reach training trials, in which the cursor motion was rotated 20° relative to hand motion (See Figure 2.2), and no-cursor reaches.

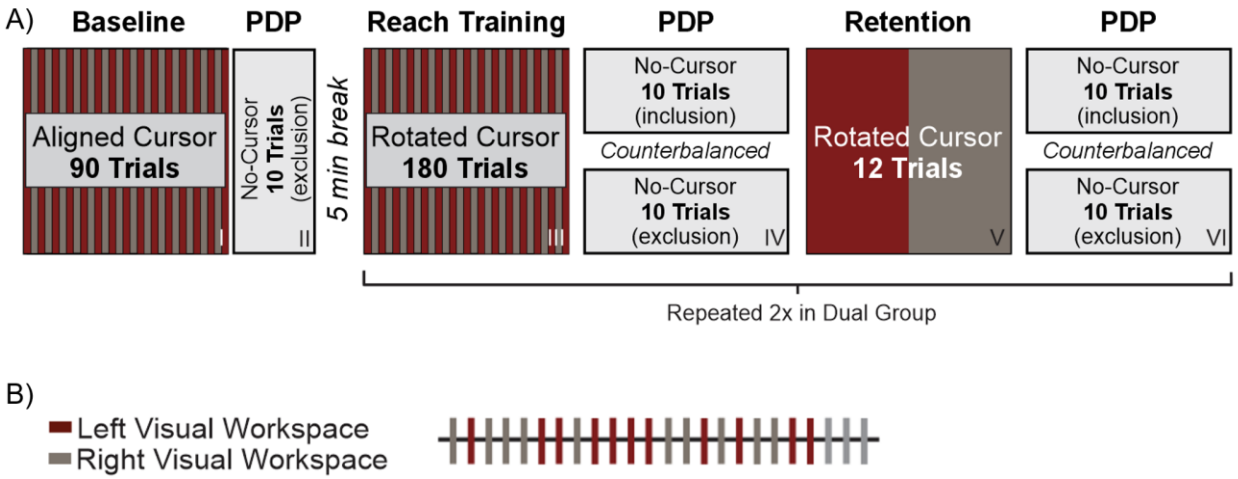


Figure 2.2 Experimental protocol and trial order

A) Experimental protocol for the Dual and Single groups. Note: garnet bars denote trials in which the left visual home position was presented, and grey bars denote trials in which the right visual home position was presented. In both the Dual and Single adaptation protocols, inclusion and exclusion trials were completed in both the left and right visual workspaces. B) Example trial order during aligned and rotated reach training. Each garnet line represents one set of 3 trials completed within the left visual workspace and each grey line represents one set of 3 trials completed within the right visual workspace. Reach training trials were completed such that there was a minimum of 3 trials to a maximum of 12 trials completed within one visual workspace before switching.

Types of trials

Baseline training: Familiarization and aligned reach training trials

During the baseline phase, both groups started with familiarization trials. In these trials, participants grasped the robot handle and reached from the hand home position. The home position for the hand was located in the middle of the workspace, approximately 20 cm in front of the participant and in line with their midline. Visual home positions (i.e., circles 1 cm in diameter) were translated 15 cm to the left and right of the hand home position. Half of the participants in each group started reaching when seeing the visual home position, target and cursor presented in the left side of the workspace, while the other half of the participants in each group started reaching when seeing the visual home position, target and cursor presented in the right side of the workspace. The visual display alternated between the left and right visual workspaces every 3 trials, such that participants completed 12 familiarization trials in total. Specifically, participants completed 4 sets of 3 reaches to a target located 12 cm directly in front of the left and right visual home positions as shown in Figure 2.1B. Note that to achieve this target location, participants had to reach 12 cm forwards from the hand home position.

The aligned reach training trials were the same as the familiarization trials such that cursor feedback was aligned with participants' hand motion with respect to direction but translated 15 cm left or right relative to hand position. Thus, the cursor was displayed in the left or right visual workspace, just as in the familiarization trials. Half of the participants started when seeing the left (or right) visual home position. Participants completed 30 sets of 3 reaches (15 sets from each visual home position), randomly switching between the left and right visual workspaces for a total of 90 aligned reach training trials. Note that a minimum of 1 set of 3 reaches (i.e., 3 trials) and a maximum of 4 sets of 3 reaches (i.e., 12 trials) were completed from the same visual home position before the visual home position switched (see Figure 2.2B).

Each trial started with the appearance of the target (yellow circle, 2 cm in diameter). Participants were instructed to reach to the target with the goal of having the cursor (magenta circle, 1 cm in diameter) land on the target. Participants saw real-time visual feedback of their hand position via the cursor on the screen throughout their movement. Once the cursor landed on the target, such that the middle of the cursor fell within 5 mm of the center of the target, the target disappeared, and the robot passively moved the hand back to the home position following a direct, linear path in a movement time of 1000 ms. If participants attempted to move outside of the linear path, a resistance force (proportional to the depth of penetration with a stiffness of 2 N/mm and a viscous dampening of 5 N/mm) perpendicular to the grooved path was produced. The position of the KINARM robot was recorded at a sampling rate of 1000 Hz, with a spatial accuracy of 0.1 mm.

Adaptation training: Rotated reach training

The adaptation phase proceeded in a similar manner to the baseline phase. However, during the rotated reach training trials, participants reached while experiencing a 20° CW and CCW cursor rotation (Dual group), or a 20° CW or 20° CCW cursor rotation (Single group) (see Figure 2.2). In the Dual group, when the left visual home position was displayed, the cursor motion was rotated CW relative to hand motion and when the right visual home position was displayed, the cursor motion was rotated CCW relative to hand motion. For the Single group, half of the participants reached with either a CW or CCW cursor rotation during rotated reach training trials, no matter which visual home position was displayed. In the Dual group, participants performed 60 sets of 3 trials and in the Single group, participants performed 30 sets of 3 trials. A minimum of 1 set of 3 trials and a maximum of 4 sets of 3 trials were completed from the same visual home position before the visual home position switched.

No-cursor reaches

The no-cursor reaches consisted of *exclusion* and *inclusion* trials. Only *exclusion* trials were completed following aligned reach training trials in the Baseline phase (Figure 2.2A, Box II). In these trials, participants were instructed as follows:

"You are now going to reach when you cannot see your hand, as there will be no-cursor on the screen. For these trials, reach so that your hand goes straight to the target as you did during baseline".

Ten *exclusion* trials were completed in one block, such that participants reached five times in the left and right visual workspace. The order in which the visual home position (i.e., left or right visual home position) was presented during the no-cursor reaches was counterbalanced across participants.

Following rotated reach training, participants performed exclusion and inclusion trials. Participants in the Dual group performed the exclusion and inclusion trials twice, whereas the Single group performed these trials once. The order of exclusion and inclusion trials was pseudo-randomized across participants with respect to which type of trial they completed first (i.e., half of the participants started with exclusion trials, while the other half of the participants started with inclusion trials; see Figure 2.2A, Box IV & VI). In the inclusion trials, participants were instructed:

"You are now going to reach when you cannot see your hand, as there will be no-cursor on the screen. For these trials, use anything you have learned during training in order to get the cursor to the target. In other words, reach so that the cursor would have gone straight to the target, as in the training trials you just completed."

In the exclusion trials, participants were given the same instructions as mentioned above.

In between blocks of exclusion and inclusion trials following rotated reach training, participants performed 12 rotated reach training trials to ensure visuomotor adaptation was maintained. For both groups, the visual home position displayed alternated after two sets of three rotated reach training trials until all 4 sets (12 trials) of reaches were completed.

Data analysis

All trials were analyzed using custom-written MATLAB scripts (Matlab R2019). The start (movement onset) and end (movement termination) of each reach were selected based on a velocity criterion, such that movement onset and movement termination were defined as when velocity of the reach first increased above or decreased below 0.01 m/s for 100 ms, respectively. The reaching error for each trial was calculated as the angular error of the hand at peak velocity (i.e., PVAE), where PVAE is equal to the angular difference between a vector from the home position to the desired target and a vector from the home position to the hand's actual position at peak velocity. If participants reached so that the cursor went directly to the target, PVAE would be minimal (i.e., 0°) in the aligned reach training trials and approximately 20° in the rotated reach training trials to account for the visuomotor distortion.

If participants demonstrated a mean PVAE greater than 25° in the baseline reach training phase and greater than 50° in the adaptation reach training phase, the participant was removed from the analyses discussed below. This resulted in the exclusion of five participants (i.e., 4 participants from the Dual group and 1 participant from the Single group who reached with a CW rotation). Individual trials were removed from the remaining participants if PVAE was greater than 25° in an aligned reach training trial and greater than 50° in a rotated reach training

trial. Based on this cut-off criteria, a total of 121 trials (1.5% of all trials included in our analyses), were removed. Results did not differ with the inclusion of these trials.

Reach training trials

For analyses, we considered the Single group as two distinct groups, a Single CW and Single CCW group. As well, when analyzing reaching errors during the adaptation phase, we refer to the Dual group as Dual 180 or Dual 360 (Dual 180: which consisted of the first 180 trials completed by the Dual group and Dual 360: which consisted of the second set of 180 trials completed by the Dual group), to establish any changes in visuomotor adaptation with additional training trials.

To establish baseline errors during the aligned reach training trials the average PVAE for the last 20 aligned reach training trials to targets in the left and right visual workspaces were compared across groups using a 3 Group (Single CW, Single CCW, Dual) x 2 Visual Workspace (Left, Right) mixed analysis of variance (ANOVA) with repeated measures (RM) on the last factor. Next, mean PVAE of the last 20 rotated reach training trials in each visual workspace were normalized by subtracting the mean PVAE of the aligned reach training trials in the corresponding visual workspace. To ensure all normalized reaching errors for rotated reach training trials were in a similar direction across groups, all negative values (leftward direction errors) were multiplied by -1. Mean PVAE were first analyzed in 2 Training Trial (Dual 180, Dual 360) x 2 Visual Workspace (Left, Right) RM ANOVA to establish any changes in adaptation with additional training in the Dual group. This was followed by a 3 Group (Single CW, Single CCW, Dual 360) x 2 Visual Workspace (Left, Right) mixed ANOVA, with RM on the last factor.

No-cursor trials

First, we looked to determine if there was any evidence of explicit adaptation by comparing mean PVAE on exclusion and inclusion trials in the adaptation phase. Performance in the Dual group was compared across training trials in a 2 Training Trial (Dual 180, Dual 360) x 2 Trial Type (Inclusion, Exclusion) x 2 Visual Workspace (Left, Right) RM ANOVA. Following this analysis, exclusion and inclusion trials were compared in a 3 Group (Single CW, Single CCW, Dual 360) x 2 Trial Type (Inclusion, Exclusion) x 2 Visual Workspace (Left, Right) mixed ANOVA with RM on the last 2 factors. As indicated in the results section, both ANOVAs revealed no significant main effect of trial type or interaction involving the factor of trial type, thus, subsequent analysis focused on comparing implicit adaptation across groups.

We first determined the implicit index for each visual workspace using exclusion trials following rotated reach training according to the formula:

$$\text{Implicit index (II)} = M_{\text{PVAE on exclusion trials}}$$

where M_{PVAE} represents the average PVAE within an exclusion block of trials for reaches completed in the left or right visual workspace (Figure 2.2A, Block IV & VI). Implicit indexes were then normalized by mean PVAE of exclusion trials during the baseline phase to establish implicit adaptation. To determine if implicit adaptation increased with training trials in the Dual group, normalized implicit indexes were first analyzed in 2 Training Trial (Dual 180, Dual 360) x 2 Visual Workspace (Left, Right) RM ANOVA. The extent of implicit adaptation was then compared across groups in a 3 Group (Single CW, Single CCW, Dual 360) x 2 Visual Workspace (Left, Right) mixed ANOVA, with RM on the last factor. Lastly, to establish that the Dual group did indeed exhibit implicit adaptation after 180 trials, implicit adaptation for the Dual

180 group was analyzed in a 2 Phase (Baseline, Adaptation) x 2 Visual Workspace (Left, Right) RM ANOVA.

ANOVAs were conducted in SPSS, version 29, and corresponding *p* values and effect sizes are reported below. The significance value for all ANOVAs was set at $p < 0.05$, and Bonferroni tests corrected for multiple comparisons were used for all pre-planned comparisons.

Results

Visuomotor adaptation

Participants first completed aligned reach training trials in the baseline phase. As shown in Figure 2.3A, PVAE in the left visual workspace was lower than in the right visual workspace for all groups during aligned reach training, indicating that participants reached more accurately when the target in the left visual workspace was displayed. In accordance with this observation, ANOVA revealed a significant main effect of Visual Workspace ($F(1, 51) = 108.82$, $p = 0.001$, $\eta^2 = 0.68$), such that participants reached with a larger PVAE (M = -6.07°, SE = 0.34°) when the target was displayed in the right visual workspace compared to the left visual workspace (M = -2.41°, SE = 0.31°). There was no significant main effect of Group ($F(2,51) = 0.58$, $p = 0.56$, $\eta^2 = .022$) and no significant Group x Visual Workspace interaction ($F(2,51) = 1.22$, $p = 0.30$, $\eta^2 = 0.05$).

In Figure 2.3B and 2.4 we present data for participants during the rotated reach training trials in the adaptation phase. To determine if visuomotor adaptation differed between groups, we looked at the normalized mean PVAE at the end of the rotated reach training trials. First, we assessed for any differences in adaptation within the Dual group after 180 and 360 training trials. ANOVA revealed a significant main effect of Training Trial ($F(1,25) = 16.61$, $p = 0.001$, $\eta^2 = 0.40$) and a main effect of Visual Workspace ($F(1, 25) = 7.55$, $p = 0.01$, $\eta^2 = 0.23$). However, there was no significant interaction between Training Trial and Visual Workspace ($F(1, 25) = 0.72$, $p = 0.40$, $\eta^2 = 0.03$). Visuomotor adaptation in the Dual group increased with additional reach training trials (i.e., after 360 trials, the Dual group demonstrated greater visuomotor adaptation than after performing 180 trials) and was greater in the right visual workspace compared to the left visual workspace.

Following this, we compared adaptation across groups, using the extent of visuomotor adaptation achieved for the Dual group after 360 training trials. ANOVA revealed a significant main effect of Group ($F(2,51) = 11.17$, $p = 0.001$, $\eta^2 = 0.31$), no significant main effect of Visual Workspace ($F(1,51) = 3.92$, $p = 0.53$, $\eta^2 = 0.07$) and a significant interaction of Group x Visual Workspace ($F(2, 51) = 3.77$, $p = 0.03$, $\eta^2 = 0.13$). Post-hoc analysis revealed that the Single CCW group (M = 19.12°, SE = 0.41°) demonstrated significantly greater visuomotor adaptation in the left visual workspace compared to the Dual group (M = 15.38°, SE = 0.71°, $p = 0.001$). There were no significant difference between the Single CCW group and Single CW group (M = 17.21°, SE = 0.53°, $p = 0.14$), or between the Single CW group and the Dual group (p = 0.089) in the left visual workspace. In the right visual workspace, the Single CCW group (M = 20.58°, SE = 0.83°) demonstrated significantly greater visuomotor adaptation than the Single CW (M = 16.34°, SE = 0.63°, p = 0.006). Adaptation in the Single CCW group did not significantly differ from the Dual group in the right visual workspace (M = 18.51°, SE = 0.59°, $p = 0.23$).

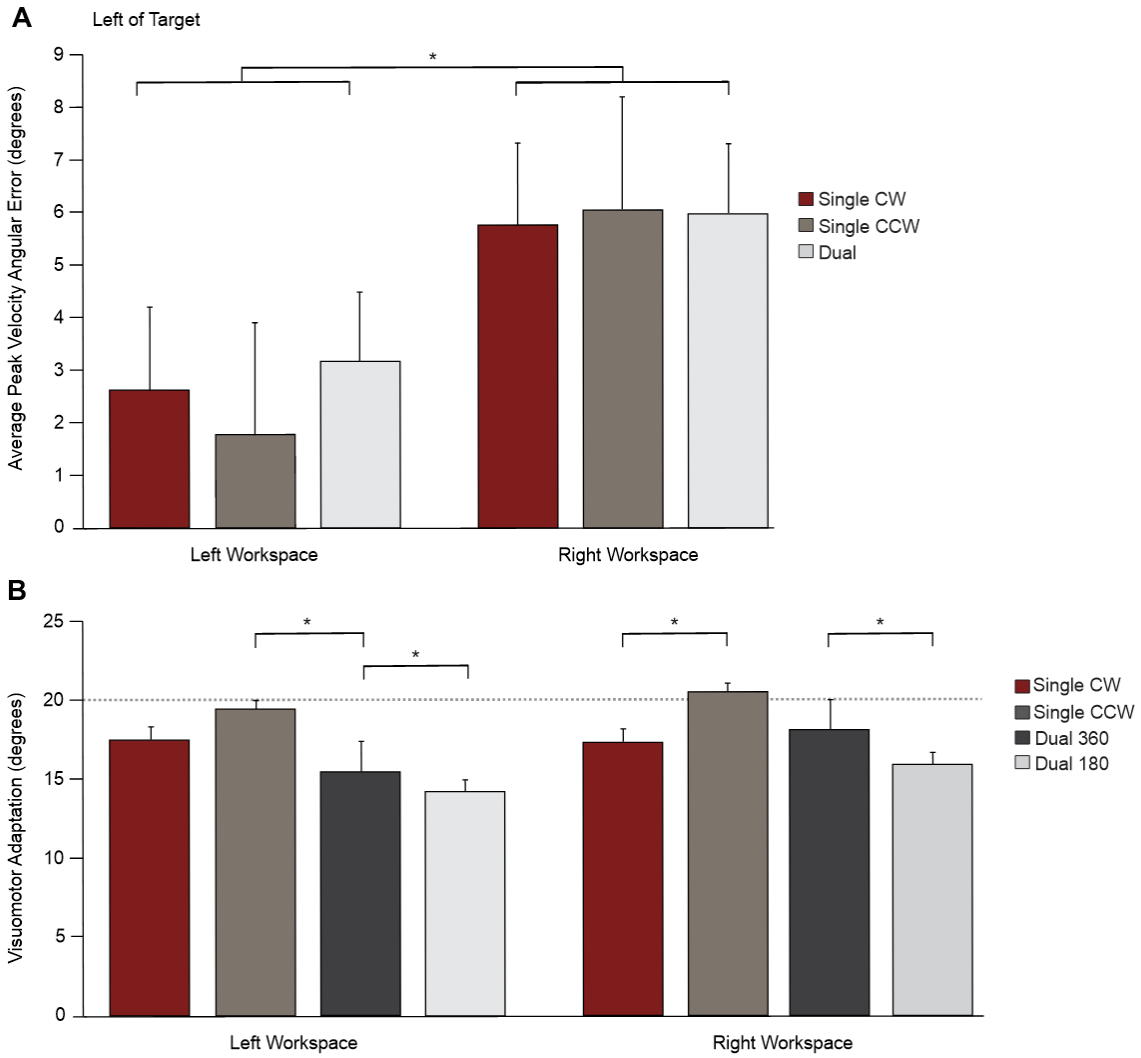


Figure 2.3 Visuomotor adaptation

A) Mean angular error at peak velocity in degrees during aligned reach training trials for both the left and right visual workspaces (positive values indicate errors to the left of the target) for the Single CW, Single CCW and Dual groups. B) Visuomotor adaptation in degrees during rotated reach training trials relative to aligned reach training trials for both the left and right visual workspaces for all groups. Values closer to 20° represent more accurate reaches. Garnet bars indicate reaching errors for the Single CW group, medium grey for the Single CCW group, dark grey for the Dual group after performing 360 trials and light grey for the Dual group after performing 180 trials. Error bars represent standard error of the mean. In (A) asterisks (*) represent significant differences between visual workspaces ($p < 0.05$) and in (B) asterisks (*) represent significant differences between groups or training trials ($p < 0.05$).

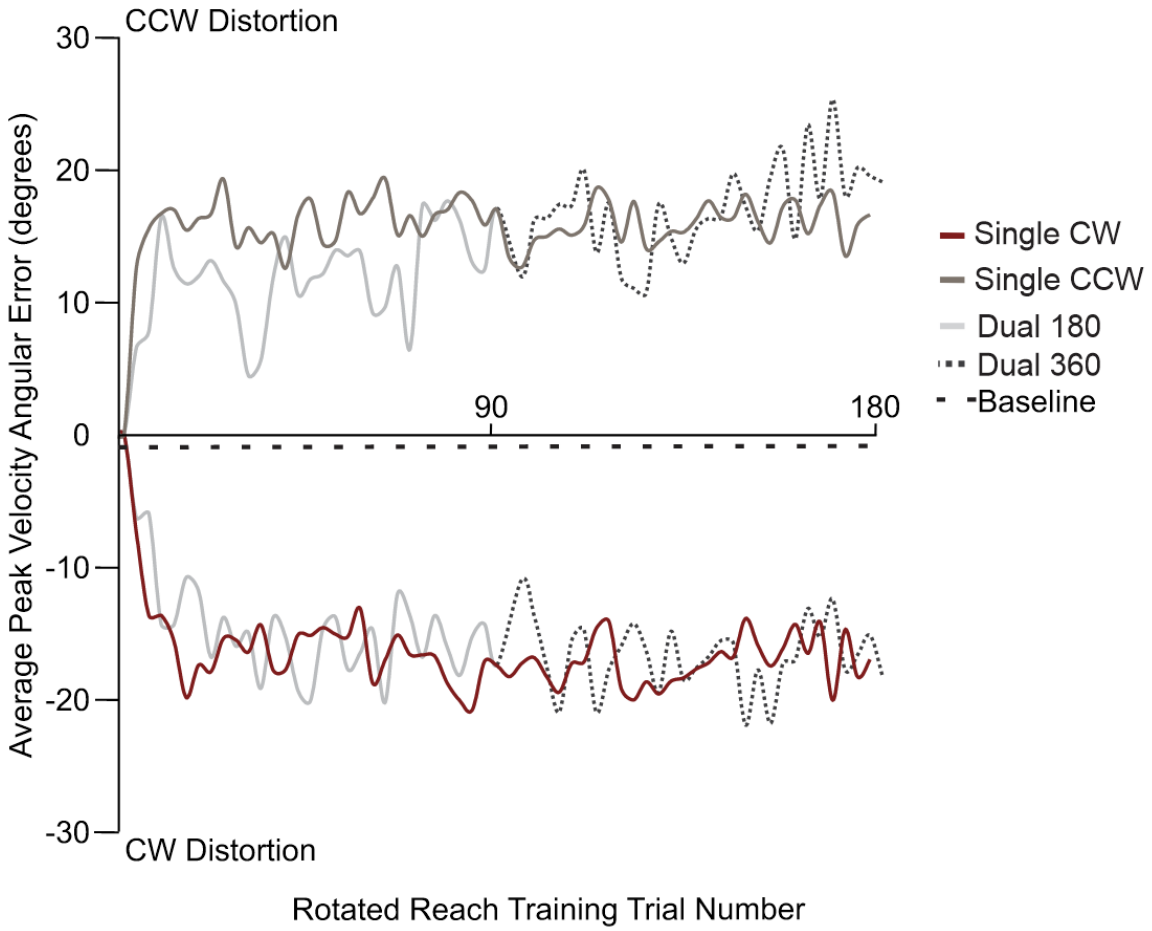


Figure 2.4 Mean hand peak velocity angular error (PVAE) across the rotated reach training trials

Data displayed are the average PVAE of 3 trials for 1 participant in each group over 180 rotated reach training trials. The garnet line indicates visuomotor adaptation for the Single CW participant, medium grey for the Single CCW participant, light grey for the Dual participant over the first 180 rotated training trials and dotted dark grey for the Dual participant over the last 180 rotated training trials. Average PVAE across all aligned reaches is demonstrated by the black dotted line.

No-cursor trials

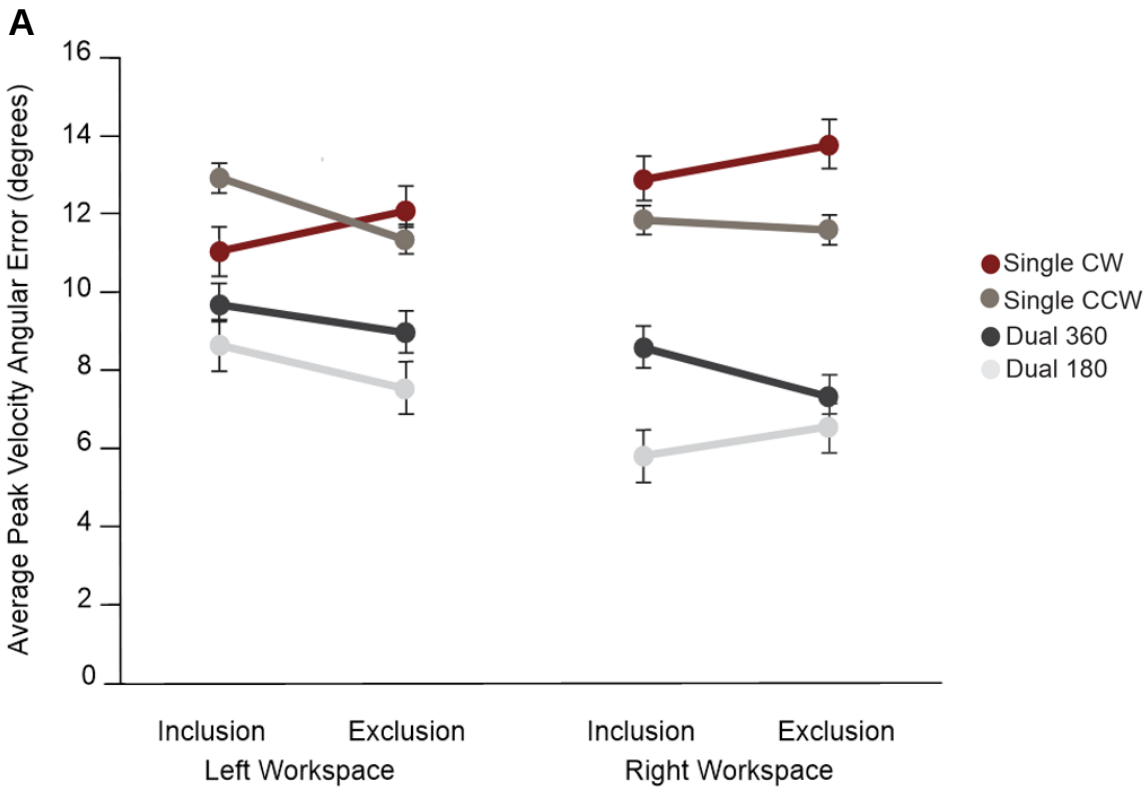
PVAE in the left (M = -3.31°, SE = 0.62°) and right visual workspaces (M = -3.80°, SE = 0.74°) did not differ across Groups during baseline exclusion trials ($F(2,51) = 0.22$, $p = 0.81$, $\eta^2 = 0.012$). ANOVA also revealed no significant main effect of Visual Workspace ($F(1,51) = 0.29$, $p = 0.59$, $\eta^2 = 0.006$) and no significant interaction ($F(2,51) = 0.29$, $p = 0.74$, $\eta^2 = 0.012$).

In Figure 2.5A, we show mean PVAE of inclusion and exclusion trials for the left and right visual workspaces. First, we compared trials for the Dual group after 180 and 360 reach training trials. RM ANOVA revealed Inclusion (M = 8.11°, SE = 0.99°) and Exclusion (M = 7.51°, SE = 0.63°) trials did not differ significantly ($F(1, 25) = 0.44$, p = 0.51, $\eta^2 = 0.02$), nor was there any significant interactions involving Trial Type (all p > 0.21). When comparing PVAE across trial types for all three groups, we found no significant main effect of Trial Type ($F(1, 51) = 0.18$, p = 0.68, $\eta^2 = 0.003$) or any significant interactions involving Trial Type (all $p > 0.51$). These results suggest that participants did not adapt their reaches explicitly. Based on these results, we next focused on comparing the extent of implicit adaptation across groups.

With respect to implicit contributions, we first examined differences in the Dual group across training trials. ANOVA revealed no significant main effect of Trial Number ($F(1,25) = 1.06$, $p = 0.31$, $\eta^2 = 0.04$) or Visual Workspace ($F(1,25) = 0.93$, $p = 0.34$, $\eta^2 = 0.04$), and no significant interaction ($F(1,25) = 0.72$, $p = 0.404$, $\eta^2 = 0.03$). When comparing means across groups, ANOVA revealed a significant main effect of Group ($F(2,51) = 4.78$, $p = 0.013$, $\eta^2 = 0.16$), but no significant main effect of Visual Workspace ($F(2,51) = 0.01$, $p = 0.94$, $\eta^2 = 0$) or significant Group x Visual Workspace interaction ($F(2,51) = 0.70$, $p = 0.50$, $\eta^2 = 0.03$) were found. Post hoc analysis revealed that implicit adaptation in the Single CW group (M = 13.03°, SE = 2.0°) and the Single CCW group (M = 11.52°, SE = 1.96°), did not differ from each other

(p = 1). As shown in Figure 2.5B, implicit adaptation for the Dual group after 360 trials did not differ significantly from the Single CCW group (p = 0.15) but was less than the Single CW group (p = 0.02).

Lastly, we looked to establish that the Dual group did indeed exhibit implicit adaptation after performing 180 rotated reach training trials. ANOVA revealed a significant main effect of Phase (F(1,25) = 96.28, p = 0.001, η^2 = 0.79), confirming that the Dual group demonstrated implicit adaptation. There was no significant main effect of Visual Workspace (F(1,25) = 0.10, p = 0.76, η^2 = 0.004) or interaction of Phase x Visual Workspace (F(1,25) = 0.34, p = 0.56, η^2 = 0.014. These results indicate that all groups demonstrated implicit adaptation.


A
Average Peak Velocity Angular Error (degrees)
16
14
12
10
8
6
4
2
0
Inclusion
Exclusion
Inclusion
Exclusion
Left Workspace
Right Workspace
Single CW
Single CCW
Dual 360
Dual 180

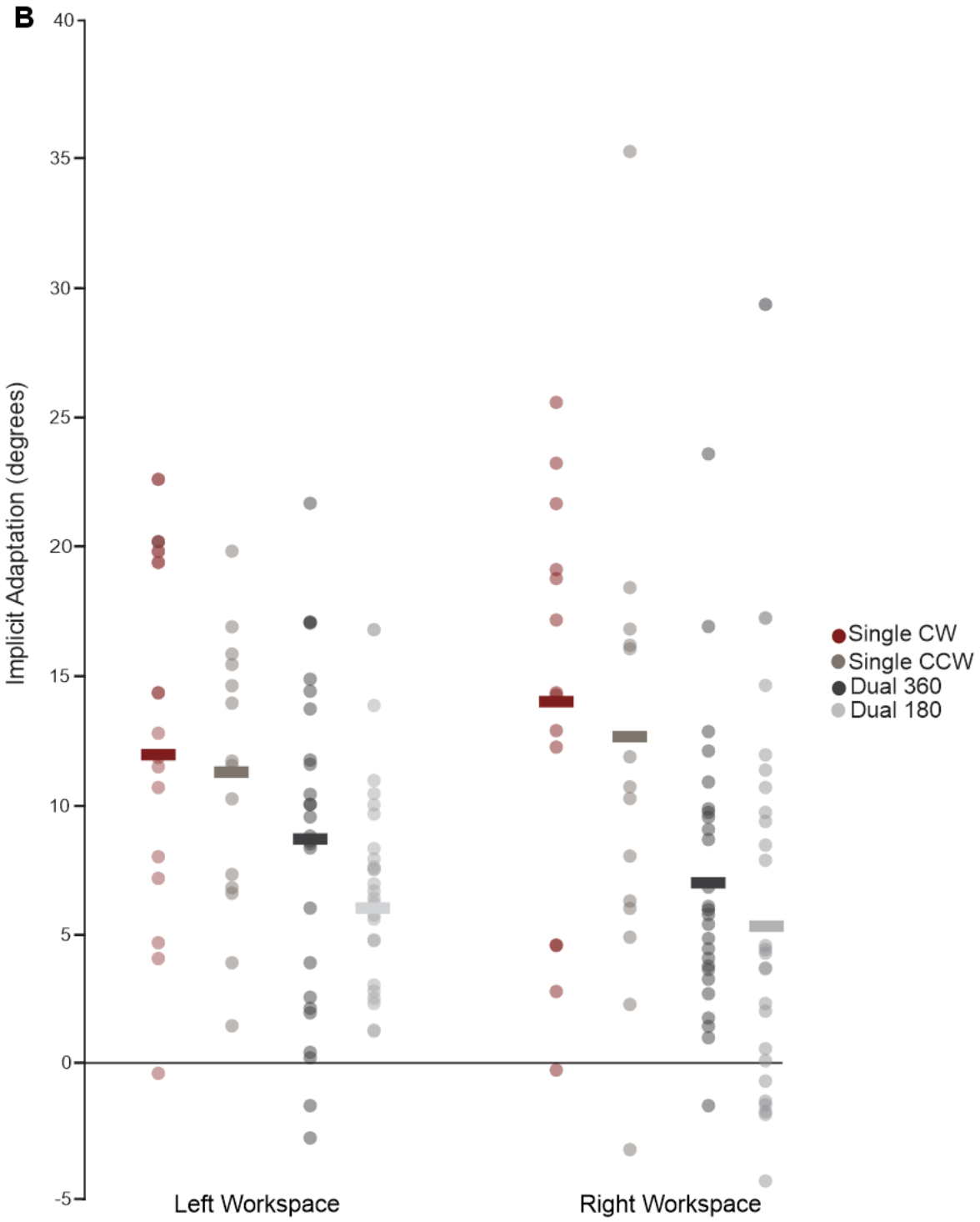


Figure 2.5. Implicit and explicit adaptation

A) Mean normalized peak velocity angular error (PVAE) of inclusion and exclusion trials in the left and right visual workspaces. B) Mean implicit adaptation represented as sold lines in both the left and right visual workspaces, with individual participant values shown as dots. Garnet

dots indicate mean reaching errors for the Single CW group, medium grey for the Single CCW group, dark grey for the Dual 360 group and light grey for the Dual 180 group.

Discussion

In the current experiment, participants reached with two small (i.e., 20°) opposing cursor rotations in a dual visuomotor adaptation paradigm to establish the involvement of implicit and explicit processes to dual visuomotor adaptation. Reaching performance was compared to participants in a Single group, who reached with a single 20° CW (or CCW) cursor rotation to targets in the left and right visual workspaces. For the Dual group, the cursor rotation imposed was dependent on the visual workspace in which the target was presented, such that when the target was in the left visual workspace, cursor feedback was rotated 20° CW relative to hand motion, and when the target was in the right visual workspace, cursor feedback was rotated 20° CCW relative to hand motion. For all participants, implicit and explicit contributions underlying visuomotor adaptation were assessed using the Process Dissociation Procedure (PDP; Neville & Cressman, 2018; Werner et al., 2015). Results indicated that when reaching to targets presented in the left and right visual workspaces, dual visuomotor adaptation arose, such that participants in the Dual group demonstrated errors in the opposite direction of the cursor rotation for each visual workspace. There was no evidence of explicit adaptation for the Dual or Single groups. However, we did find evidence of implicit adaptation across all groups. Participants in the Single CW group demonstrated greater implicit adaptation than the Dual group following 360 reach training trials, while implicit adaptation in the Dual group did not differ from participants who trained with a Single CCW cursor rotation. These results confirm that implicit adaptation does underlie both dual and single visuomotor adaptation when adapting to small cursor rotations.

Dual visuomotor adaptation

Previous dual visuomotor adaptation studies have shown that participants can adapt their reaches to two opposing cursor rotations (i.e., CW and CCW cursor rotations) depending on the

cue used to signal the direction of the visuomotor distortion (see Ayala et al., 2015; Hegele & Heuer, 2010; Hinder et al., 2007; Woolley et al., 2007). Task-irrelevant cues, such as changes in target or background colour to signal different visuomotor rotations have led to inconclusive results regarding dual visuomotor adaptation (Baldeo & Henriques, 2013; Hegele & Heuer, 2013; Osu et al., 2004; Woolley et al., 2007). In contrast, dual visuomotor adaptation has been shown to be facilitated when the opposing visuomotor distortions are cued through task-relevant cues (Hegele & Heuer, 2013; Schween et al., 2018; Woolley et al., 2007). Task-relevant cues allow the sensorimotor system to identify and associate changes that occur within the environment with the appropriate motor command for task-success (Schween et al., 2018). An example of a task-relevant cue is signalling the different visuomotor distortions by the visual workspace in which the target is presented (i.e., targets presented in the left visual workspace are associated with a CW rotation and targets presented in the right visual workspace are associated with a CCW rotation; see Hegele & Heuer, 2013; Schween et al., 2018; Wang & Müsseler, 2014).

Given the consistent findings of dual visuomotor adaptation using this visual workspace cue manipulation, we cued our two opposing cursor rotations by presenting targets in the left (i.e., cued CW cursor rotation) and right (i.e., cued CCW cursor rotation) visual workspaces. Our results agree with previous findings in which large opposing cursor rotations were cued through visual workspace location (i.e., cursor rotations greater than 45°; see Hegele & Heuer, 2010; Heuer & Hegele, 2008; Schween et al., 2018), as participants demonstrated dual visuomotor adaptation. This study is one of the first to demonstrate successful facilitation of dual adaptation to opposing small cursor rotations (see also Bernier et al., 2023), where small cursor rotations are considered less than 30° (Modchalingam et al., 2019; Neville & Cressman, 2018; Werner et al.,

2015). Furthermore, this study shows an increase in dual visuomotor adaptation with increased training trial number.

Additionally, our study provides insight into dual visuomotor adaptation compared to single visuomotor adaptation. We treated our Single group of participants as two separate groups, a Single CW group and Single CCW group, given differences observed across visual workspaces with respect to reach training errors during the baseline phase and differences in the extent of visuomotor adaptation across visual workspaces. When examining the reaching errors in the aligned reach training trials, we found that participants reached left of the target, regardless of whether it was displayed in the left or right visual workspace. Reaching errors were larger when the target was presented in the right visual workspace compared to the left visual workspace. These leftwards reaching errors could be due to a perceived hand bias. Previous work by Jones and colleagues (2010) had participants localize their left and right hand positions in the absence of vision. Results demonstrated that participants perceived their right hand to be more rightward and their left hand to be more leftward than they actually were. This hand bias was then reflected in participants' reaches, such that the right hand reached to the left of the target (Jones et al., 2010). Our findings are in agreement with Jones and colleagues (2010), demonstrating a leftward reaching error when participants reached with aligned cursor feedback in both visual workspaces, however, why there were greater reaching errors made when reaching with a target displayed in the right versus left visual workspace is unclear.

Differences in visual workspace were further observed for the Dual group during the adaptation phase and trended towards significance when the Single groups were included in our analysis. Specifically, we found that visuomotor adaptation was greater for the Dual group when the target was presented in the right visual workspace compared to the left visual workspace

when PVAE was normalized to aligned baseline reaches. We tested if this difference was due to initial reaching errors experienced during aligned reach training trials by comparing reaching errors during visuomotor adaptation trials that were not normalized to aligned reach training errors. In general, participants reached 17.6º away from the target in the left visual workspace and 11.1º away from the target in the right visual workspace, which significantly differed (p = < 0.001). This larger deviation from the target presented in the left visual workspace, demonstrates that one's that leftward perceived natural hand bias (as observed in aligned reach training) impacts the extent of visuomotor adaptation observed.

Furthermore, regarding the impact of the direction of the cursor rotation on visuomotor adaptation, we found that participants in the Single CCW group demonstrated a greater extent of visuomotor adaptation than the Single CW group. From the preceding paragraph, we know that the Dual group demonstrated greater visuomotor adaptation when the target was presented in the right visual workspace and the CCW cursor rotation was cued. Together, these results indicate that visuomotor adaptation to a CCW cursor rotation requiring a rightward reaching movement is greater than visuomotor adaptation to a CW cursor rotation requiring a leftward reaching movement. We are unaware of any research examining the differences in visuomotor adaptation to CW versus CCW rotations (in a single visuomotor adaptation paradigm). Thus, at this time we can only suggest that the differences in visuomotor adaptation to the different cursor rotations arose because of participants' initial hand/reaching bias. At this time, this is merely a suggestion. Future research should take caution in assuming that visuomotor adaptation is similar when CW and CCW cursor rotations are presented, and collapsing results across the different cursor rotations, as done previously (e.g., Ayala & Henriques, 2021; Baldeo & Henriques, 2013), as our

results indicate that the location of target presentation within the workspace and the direction of the cursor rotation impacts the extent of visuomotor adaptation achieved.

Mechanisms underlying dual visuomotor adaptation

Having established that participants in the Dual and Single groups adapted their reaches to the cursor rotation(s), we next looked to establish implicit and explicit contributions underlying dual visuomotor adaptation. We found that for all groups, visuomotor adaptation arose implicitly. These results for our Dual group are in contrast to previous findings demonstrating that explicit processes are primarily responsible for dual visuomotor adaptation (Hegele & Heuer, 2010; Schween et al., 2018). For example, Hegele and Heuer (2010) showed that explicit processes drove dual visuomotor adaptation when young and older adults adapted their reaches to opposing 75° visuomotor rotations (see also Schween et al., 2018). With the use of a large visuomotor distortion, it is expected that participants will become aware of the changes within their environment, leading to explicit adaptation (Neville & Cressman, 2018; Werner et al., 2015). Thus, it is perhaps not surprising that explicit adaptation was found to drive dual visuomotor adaptation in previous studies in which participants adapted their reaches to two large opposing visuomotor distortions.

We are aware of only two other studies that have examined dual adaptation to small opposing cursor rotations (30°). Ayala and Henriques (2021) had participants adapt their reaches to two opposing 30° cursor rotations when the different rotations were cued with contextual cues (left target box displayed: CW rotation and right target box displayed: CCW rotation) in the same visual workspace. In this study, Ayala and Henriques (2021) did not find evidence of implicit contributions to dual visuomotor adaptation. Additionally, they found no evidence of dual visuomotor adaptation even when the cursor was present. More recently, Bernier and

colleagues (2023) assessed implicit contributions to multiple cursor perturbations. Specifically, they had participants adapt their reaches to five separate targets, where each target was associated with a 5° CW or CCW cursor rotation or no cursor rotation. Results indicated that participants were able to fully compensate for the imposed cursor rotations, even though they were unaware of the perturbations. Based on these results the authors concluded that dual visuomotor adaptation arose implicitly. In agreement with the findings of Bernier et al. (2023), we found that dual visuomotor adaptation was driven implicitly in the current study. We further show that there was no contribution of explicit processes underlying dual visuomotor adaptation, findings that differ from Hegele and Heuer (2010) and Schween et. al., (2018). Considering our results in light of previous findings, it appears that explicit processes are engaged when participants are aware of the relevant changes between the cue and the transformation (i.e., target presented in the left visual workspace associated with a large CW rotation and target presented in the right visual workspace associated with a large CCW). When a rotation is small (e.g., 20° or less), explicit processes are not engaged, even when participants are aware of a physical separation of visual targets into different workspaces.

When adapting to one single small visuomotor rotation (i.e., less than 30°), it has been established that visuomotor adaptation is driven by implicit processes (Modchalingam et al., 2019; Neville & Cressman, 2018; Werner et al., 2015). In the present study, we also found that visuomotor adaptation arose implicitly for participants in the Single CW and CCW groups. Previous studies assessing the extent of implicit adaptation following adaptation to a single, small cursor rotation found aftereffects in the range of 6° to 12° (Bond & Taylor, 2015; Neville & Cressman, 2018). Here, we found implicit adaptation to be in the range 7° to 13° for both of our Single groups and our Dual group.

Implicit adaptation occurred across all groups, but not to the same extent. The Single CW group demonstrated significantly greater implicit adaptation when compared to the Dual group after they completed 360 rotated reach training trials. Our results further show that following 360 rotated reach training trials the Dual group was able to reach similar levels of implicit adaptation as the Single CCW group. This finding partially agrees with our hypothesis that implicit adaptation occurs to a similar extent between Single and Dual groups under the condition that the Dual group required additional training trials. However, it is unclear why the Dual 360 group did not reach similar levels of implicit adaptation as the Single CW group.

Recent research has suggested that implicit adaptation has a limit (Albert et al., 2021; Neville & Cressman, 2018). According to state-space models of adaptation, this ceiling effect arisese due to the interaction between learning and forgetting (Albert et al., 2021, Morehead & Smith, 2017). Specifically, the ceiling for implicit adaptation is when learning and forgetting are in equilibrium (Morehead & Smith, 2017). Therefore, it is possible that the two internal models within the Dual group do not reach the same ceiling for implicit adaptation due to an increase in forgetting for one internal model. However, we saw that the Dual group demonstrated an extent of implicit visuomotor adaptation that did not differ from the CCW group following 360 trials, thus, it is possible that with additional adaptation trials (i.e., 540 rotated reach training trials), the relationship between learning and forgetting could come into equilibrium for both cursor rotations and that implicit adaptation could increase to a similar magnitude as seen in the Single CW group.

Interestingly, compared to our visuomotor adaptation results, we did not find differences between the two cursor rotation directions (i.e., implicit adaptation did not differ for participants who trained with a Single CW versus Single CCW cursor rotation). Similarly, there was no

difference in implicit adaptation across the visual workspaces. These results suggest that more complete visuomotor adaptation observed during reach training does not result in greater implicit adaptation, supporting Bond and Taylor's (2015) proposal that implicit adaptation is limited.

Summary

Dual visuomotor adaptation has been shown to be facilitated using task-relevant cues, such as cueing the opposing cursor rotations by presenting targets in the left or right visual workspace (i.e., cuing a CW and CCW cursor rotation respectively). Here, we asked if dual visuomotor adaptation arises implicitly when adapting one's reaches to small opposing cursor rotations. Our findings show that dual adaptation is present when adapting to two small opposing visuomotor cursor rotations and that implicit processes that drive this dual visuomotor adaptation.

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Chapter III: General Discussion

The use of small cursor rotations within a single visuomotor adaptation paradigm has historically demonstrated engagement of implicit (i.e., unconscious) processes (Neville & Cressman, 2018; Werner et al., 2015). Here, we asked if adapting reaches to two opposing small cursor rotations would also arise implicitly. We had a group of participants complete a dual visuomotor adaptation paradigm in which they had to adapt their reaches to two opposing 20° cursor rotations. The different cursor rotations were cued by physical location of the visual home position and target in the workspace. Specifically, there was a visual home target translated 15 cm to the left and right of the common starting hand position. The visual target appeared 12 cm in front of the visual home positions, in the right or left visual workspaces. For the Dual group, when the left visual home position was displayed, the cursor motion was rotated CW relative to hand motion and when the right visual home position was displayed, the cursor motion was rotated CCW relative to hand motion. Participants were also recruited into a Single group, where the cursor motion was rotated either 20° CW (Single CW) or 20° CCW (Single CCW) relative to hand motion when the left and right visual home positions were displayed. All three groups completed a series of no-cursor reaches to assess the contributions of implicit and explicit contributions to dual visuomotor adaptation. Specifically, the Process Dissociation Procedure (PDP), adopted by Werner (2015) was used to assess implicit and explicit contributions to visuomotor adaptation, such that participants were asked to either use (inclusion trials) or withhold from using (exclusion trials) any strategy they had learned when reaching in the absence of cursor feedback, with the assumption that conscious knowledge is controllable.

We found that all participants were able to successfully adapt their reaches to the rotated cursor feedback. Specifically, the Single CCW group demonstrated the greatest amount of visuomotor adaptation. Moreover, we found that visuomotor adaptation continued to slightly

increase with additional rotated reach training trials for participants in the Dual group. We also found that reach adaptation arose implicitly for all participants, with no explicit contributions demonstrated. Furthermore, the Dual group demonstrated similar implicit adaptation as participants in the Single CCW group. The results from the present study provide insight into the role that implicit mechanisms have in dual visuomotor adaptation.

Visuomotor rotations

We are unaware of previous research examining differences in visuomotor adaptation to CW versus CCW cursor rotations in a single visuomotor adaptation paradigm. However, dual visuomotor adaptation paradigms typically assess the ability of participants to adapt their reaches to opposing CW and CCW rotations simultaneously and compare these results to participants who trained with a CW or CCW cursor rotation only. Specifically, data is typically collapsed across participants adapting to a single CW or CCW cursor rotation (Ayala et al., 2015; Baldeo & Henriques, 2013). We initially designed the present study with the idea of collapsing data across all participants in the Single group (i.e., those who trained with a CW and CCW cursor rotation) and comparing their visuomotor adaptation to the Dual group, as previous studies have done (Ayala et al., 2015; Baldeo & Henriques, 2013). However, our initial analysis revealed that participants in the Single CW and Single CCW groups demonstrated different levels of visuomotor adaptation, such that the Single CCW group demonstrated greater visuomotor adaptation compared to the Single CW group.

Our results raise questions as to how the direction of the cursor rotation impacts visuomotor adaptation. Our results suggest that when reaching with a CCW cursor rotation, visuomotor adaptation is more complete, such that participants adapted their movements to almost the full 20° of the imposed cursor rotation compared to when reaching with a CW cursor

rotation (visuomotor adaptation = 16.78°). We also found differences in how participants adapted their reaches when introduced to a CW versus a CCW cursor rotation in our Dual group, such that adaptation was significantly greater when reaching to the target displayed in the right visual workspace (i.e., CCW rotation) compared to when reaching to the target displayed in the left visual workspace (i.e., CW rotation). The findings for our Dual group are in agreement with the results of our participants in the Single group. A potential explanation for this increased visuomotor adaptation is linked to the initial leftward reaching error observed during the aligned reach training trials, such that when participants are forced to reach in the rightward direction with the CCW cursor rotation, their initial leftward reaching error leads to a possible greater extent of visuomotor adaptation.

Future research needs to further assess potential differences in visuomotor adaptation when reaching with a CW versus CCW cursor rotation. Results from this work would enable researchers to establish whether one cursor rotation is more suited for their manipulation. It is also worth noting the importance of treating participants who reach with a CCW or CW cursor rotation as separate groups, rather than collapsing data across all participants which can lead to the misinterpretation of findings.

Implicit and explicit contributions to dual visuomotor adaptation

The contributions of implicit and explicit processes to visuomotor adaptation have been of recent interest in visuomotor adaptation research, with previous studies primarily employing a single visuomotor adaptation paradigm (Modchalingam et al., 2019; Neville & Cressman, 2018; Werner et al., 2015). These studies show that implicit processes are engaged when reaching with a small cursor rotation (i.e., ≤ 30, with minimal explicit contributions (Neville & Cressman, 2018; Werner et al., 2015). Additionally, explicit adaptation has been shown to arise when using

large cursor rotations (i.e., ≥ 40°) and/or instructions are provided to participants regarding how to counteract the perturbation (Mazzoni & Krakauer, 2006; Neville & Cressman, 2018). As such, implicit and explicit adaptation have been proposed to arise due to different error signals and in turn, be independent processes (Bond & Taylor, 2015; Mazzoni & Krakauer, 2006; Neville & Cressman, 2018; Taylor et al., 2014; Werner et al., 2015). Additional research examining the processes underlying dual visuomotor adaptation would suggest that dual visuomotor adaptation arises explicitly (Hegele & Heuer, 2013; Schween et al., 2018). For example, Hegele and Heuer (2010) indicated that the task-relevant contextual cue of visually separating the targets into a left and right visual workspace engaged separated explicit strategies but not separate implicit visuomotor mappings. Moreover, Schween and colleagues (2018) stated that explicit processes are engaged within a dual visuomotor adaptation paradigm, but not implicit processes.

In the present study, we found that implicit adaptation independently drove visuomotor adaptation when participants adapted their reaches to two (or one) small cursor rotations of 20°. Our results suggest that dual visuomotor adaptation functions similarly to single visuomotor adaptation (e.g., Modchalingam et al., 2019; Neville & Cressman, 2018; Werner et al., 2015), such that dual visuomotor adaptation arises implicitly when reaching with small cursor rotations. However, implicit adaptation was less in our Dual group of participants compared to our Single CW group after performing 360 rotated reach training trials. These findings suggest that implicit adaptation is less in dual visuomotor adaptation compared to when adapting one's reaches to a single CW cursor rotation. However, based on our experimental design and the lack of findings for implicit adaptation in the literature, it is unknown why this decreased amount of implicit adaptation occurred within the Dual group for the single CW cursor rotation.

Recent work has suggested that implicit adaptation may reach a maximum/ceiling level (Albert et al., 2021; Neville & Cressman, 2018). Moreover, results have indicated that there is a degree of inter-subject variability with respect to implicit adaptation, where implicit adaptation has been shown to range from 0° to almost 50° dependent on the size of the cursor rotation (Morehead et al., 2017; Stark-Inbar et al., 2017; Wilterson & Taylor, 2021). Individual differences should be considered within future studies when assessing implicit adaptation. Additionally, the work of Bond and Taylor (2015) suggest that implicit adaptation decays quickly, even within 20 seconds. In our experimental paradigm, the target/visual workspace presentation randomly switched every 3 reaches or up to a maximum of 12 reaches. It is possible that participants within the Dual group who had not reached to a target within the left or right visual workspace for the previous 12 reaches then demonstrated lower levels of implicit adaptation due to this proposed decay.

Another consideration for the reduced magnitude of implicit adaptation is that dual visuomotor adaptation may be considered a perturbation variance paradigm. Albert and colleagues (2021) assessed perturbation variance in visuomotor adaptation by comparing a zero-variance perturbation group, where participants experienced a constant cursor rotation (comparable to our Single group) to a high-variance group where the perturbation varied from trial-to-trial (comparable to our Dual group). They found that the high-variance perturbation schedule led to an increased magnitude of residual errors (i.e., difference between the desired movement and actual movement) in their performance during learning, which decreased the magnitude of visuomotor adaptation. Moreover, they reported limited implicit adaptation. These findings could explain why the Dual group's ability to adapt implicitly was impacted in comparison to the Single group after 180 rotated reach training trials. Future research should

consider the potential impact of a high perturbation variance schedule on implicit adaptation in a dual visuomotor adaptation paradigm, as well as the timing of when implicit adaptation is assessed.

Conclusion

In the current study we tested if implicit adaptation contributes to dual visuomotor adaptation when reaching with small 20° opposing cursor rotations. We showed that the direction of the cursor rotation impacts the extent of visuomotor adaptation achieved, such that the Single CCW group demonstrated the greatest level of visuomotor adaptation. Furthermore, we established that implicit processes were responsible for visuomotor adaptation, such that there was no indication of explicit adaptation. Future experiments within visuomotor adaptation and dual visuomotor adaptation should consider the direction of the visuomotor distortion and the amount of time spent reaching to targets (i.e., target presentation schedule) within their procedures when assessing the mechanisms underlying dual visuomotor adaptation, as we have found these may critically impact implicit adaptation when reaching with two opposing cursor rotations. For now, we conclude that implicit processes underlie visuomotor adaptation when reaching with two (or one) small cursor rotations.

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Appendix A

Edinburg Handedness Inventory

Participant #: _____ Date: _____

Please **indicate with a number (1 or 2)** your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put the number 2.

Where there is a general preference that you are more likely to use the one hand over the other, put the number 1.

If you are indifferent, put a 1 in each column (1 | 1).

Task/Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a box (lid)		
Total Checks:	LH =	RH =

Modified from:

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

Participant Form

Experiment Title: Dual Visuomotor Adaptation

For Participant to Complete:

Full Name/Pronouns: _____ Date: _____

Date of Birth: _____ Age: _____ Sex *(circle)*:M F Other

Right-Handed *(circle)*: Y N Corrected Vision *(circle)*: Y N

Testing Information

Subject Code: **Feedback Group**: Dual SCW SCCW

	Start Position
Aligned	☐ Left ☐ Right
No-cursor Exclusion 1	☐ Left ☐ Right
Rotated 180 1	☐ Left ☐ Right
No-cursor 1 ☐ Exclusion ☐ Inclusion	☐ Left ☐ Right
Rotated 12 1	☐ Left ☐ Right
No-cursor 2 ☐ Exclusion ☐ Inclusion	☐ Left ☐ Right
Rotated 180 2	☐ Left ☐ Right
No-cursor 3 ☐ Exclusion ☐ Inclusion	☐ Left ☐ Right
Rotated 12	☐ Left ☐ Right
No-cursor 4 ☐ Exclusion ☐ Inclusion	☐ Left ☐ Right

Appendix B

Experimental Script

Consent forms

Welcome to the Sensorimotor Control Lab. Before we begin any testing, I am going to have you read over some general information about the lab and the current experiment.

- Have participants read the consent form and sign it.
- Have the participants complete the Edinburgh Handedness Questionnaire.
- Experimenter records any additional identification characteristics (i.e., age, date of birth, assigned group, etc.)

General Instructions

Experimental set-up

Thank you for coming in today and agreeing to participate in my experimental study. The first thing I will get you to do is to get seated in the chair and make the proper adjustments for comfort (while grasping the handle). In this experiment, you will be performing quick but accurate reaching movements using your right hand. You will grasp the handle of the KinARM, which will track your movements. Your hand will be represented as a magenta cursor on the screen. This means you will not be able to see your actual hand underneath the screen, but you will still be able to interact with targets.

In general, your task will be to reach to the target as quickly and accurately as possible with the goal of the magenta cursor landing on the yellow target. You will reach to one of two targets. The experiment will be divided into two times separated by a mandatory 5-min break, but you are welcome to take breaks throughout the experiment. The first phase will take approximately 20 minutes to complete and the second phase will take approximately 40 minutes to complete. For every reach, you will see a visual home position on the left or right-hand side where the cursor will start. Your task will always be the same, you will reach so that the cursor will go from the visual home position to the target.

Familiarization trials

First, you will get a chance to become familiar with the set-up and stimuli. During these first trials you will have the chance to try out the movements and ask questions. You will be reaching for 12 trials. After this, data recording will begin.

Aligned Phase

The next set of trials is the baseline block consisting of trials with and without visual feedback of the cursor. It is important you remember that this block of trials is called baseline because I will refer to this block later in the experiment. You will see the start visual position and you will be reaching from the start position to the target displayed.

No-Cursor (E)

Exclusion trials: You will see the start visual position and you will be reaching from the start position to the target displayed. *In these next trials, you are now going to reach when you cannot see your hand, as there will be no-cursor on the screen. For these trials, aim so that your hand goes straight to the target as you did during baseline.*

Rotated Phase

The next set of trials is like the baseline phase consisting of trials with and without visual feedback of the cursor. First, you will be reaching with visual feedback of the cursor, as instructed previously, try to reach to the targets as quickly and as accurately as possible. You will see the start visual position and you will be reaching from the start position to the target displayed.

*No-Cursor (I)

Inclusion trials: You will see the start visual position and you will be reaching from the start position to the target displayed. *During these trials, you are now going to reach when you cannot see your hand, as there will be no-cursor on the screen. For these trials, use anything you have learned during training in order to get the cursor to the target. In other words, aim so that the cursor would have gone straight to the target, as in the training trials you just completed."*

*Rotated Cursor (2)

You will now reach with visual feedback of the cursor as you did previously. Again, you will see the start visual position and you will be reaching from the start position to the target displayed.

*No-Cursor (E)

Exclusion trials: You will see the start visual position and you will be reaching from the start position to the target displayed. *In these next trials, you are now going to reach when you cannot see your hand, as there will be no-cursor on the screen. For these trials, aim so that your hand goes straight to the target as you did during baseline.*

*Note. *Instructions will be repeated two times. The order of exclusion and inclusion trials will be counterbalanced.*

Appendix C

Ethics Approval Letter

03/05/2023

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

CERTIFICAT D'APPROBATION ÉTHIQUE | CERTIFICATE OF ETHICS APPROVAL

Numéro du dossier / Ethics File Number	H-05-21-6949
Titre du projet / Project Title	Perception of Angle Size
Type de projet / Project Type	Recherche de professeur / Professor's research project
Statut du projet / Project Status	Renouvelé / Renewed
Date d'approbation (jj/mm/aaaa) / Approval Date (dd/mm/yyyy)	03/06/2021
Date d'expiration (jj/mm/aaaa) / Expiry Date (dd/mm/yyyy)	02/06/2024

Équipe de recherche / Research Team

Chercheur / Researcher	Affiliation	Role
Erin CRESSMAN	École des sciences de l'activité physique / School of Human Kinetics	Chercheur Principal / Principal Investigator
Mary-Anne VINH	École des sciences de l'activité physique / School of Human Kinetics	Assistant de recherche / Research Assistant
Darrin WIJEYARATNAM	École des sciences de l'activité physique / School of Human Kinetics	Assistant de recherche / Research Assistant
Sarvenaz HEIRANI MOGHADDAM	École des sciences de l'activité physique / School of Human Kinetics	Co-chercheur principal / Co-principal investigator
David APREUTESEI	École des sciences de l'activité physique / School of Human Kinetics	Assistant de recherche / Research Assistant

Conditions spéciales ou commentaires / Special conditions or comments

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03/05/2023

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

Le Comité d'éthique de la recherche (CÉR) de l'Université d'Ottawa, opérant conformément à l'*Énoncé de politique des Trois conseils* (2014) et toutes autres lois et tous règlements applicables, a examiné et approuvé la demande d'éthique du projet de recherche ci-nommé.

L'approbation est valide pour la durée indiquée plus haut et est sujette aux conditions énumérées dans la section intitulée "Conditions Spéciales ou Commentaires". Le formulaire « Renouvellement ou Fermeture de Projet » doit être complété quatre semaines avant la date d'échéance indiquée ci-haut afin de demander un renouvellement de cette approbation éthique ou afin de fermer le dossier.

Toutes modifications apportées au projet doivent être approuvées par le CÉR avant leur mise en place, sauf si le participant doit être retiré en raison d'un danger immédiat ou s'il s'agit d'un changement ayant trait à des éléments administratifs ou logistiques du projet. Les chercheurs doivent aviser le CÉR dans les plus brefs délais de tout changement pouvant augmenter le niveau de risque aux participants ou pouvant affecter considérablement le déroulement du projet, rapporter tout évènement imprévu ou indésirable et soumettre toute nouvelle information pouvant nuire à la conduite du projet ou à la sécurité des participants.

The University of Ottawa Research Ethics Board, which operates in accordance with the *Tri-Council Policy Statement* (2014) and other applicable laws and regulations, has examined and approved the ethics application for the above-named research project.

Ethics approval is valid for the period indicated above and is subject to the conditions listed in the section entitled "Special Conditions or Comments". The "Renewal/Project Closure" form must be completedfour weeks before the above-referenced expiry date to request a renewal of this ethics approval or closure of the file.

Any changes made to the project must be approved by the REB before being implemented, except when necessary to remove participants from immediate endangerment or when the modification(s) only pertain to administrative or logistical components of the project. Investigators must also promptly alert the REB of any changes that increase the risk to participant(s), any changes that considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project or the safety of the participant(s).

Coordonateur / COORDINATOR
Coordonnateur de l'éthique / Ethics Coordinator
Pour/For **Daniel LAGAREC** Président(e) du/ Chair of the **Comité d'éthique de la recherche en sciences de la santé et sciences / Health Sciences and Sciences Research Ethics Board**

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