

The Influence of Awareness on Explicit and Implicit Contributions to Visuomotor Adaptation to
Different Rotation Sizes

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Statement of Contribution of Collaborators

I hereby declare that I am the sole author of this Master of Science thesis. My contributions included: a review of relevant literature in the area of interest, participant recruitment, participant testing, data collection, data analysis, data compilation, statistical analyses and the write-up of this thesis document. All of the tasks were performed under the mentorship of my research supervisor, Dr. Erin K. Cressman.

The original conception of the experiment in this thesis was performed in collaboration with my supervisor, Dr. Erin K. Cressman who provided editorial corrections and feedback, and who is the co-author in the article presented in this thesis.

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Abstract

Explicit and implicit processes play a role in visuomotor adaptation. (Bond & Taylor, 2015; Werner et al, 2015). The purpose of the current experiment was to investigate the potential contributions of explicit and implicit processes to visuomotor adaptation when awareness was manipulated directly and indirectly. To manipulate the degree of awareness directly, participants were assigned to a Strategy or No-Strategy group, in which they were made aware or remained unaware of the distortion respectively. They were then further subdivided into groups to train with a large (60°), medium (40°) or small (20°) visuomotor distortion, such that participants could become aware of the distortion indirectly with increasing sizes. All participants performed a reaching task to three targets with a cursor that was rotated clockwise relative to their hand by the assigned degrees, and then completed a series of no-cursor reaches without visual feedback to establish the contribution of explicit and implicit processes to visuomotor adaptation. Within the no-cursor reaching trials, the contribution of explicit and implicit processes to visuomotor adaptation were determined by having subjects reach (i) with any strategies they had gained during training (explicit + implicit processes), and (ii) as they did before training with the cursor rotation (implicit processes). Our results showed that the contribution of implicit processes to visuomotor adaptation was greater in the No-Strategy group compared to the Strategy group. Moreover, implicit processes took time to develop, and decayed following a 5-minute break. In contrast, the contribution of explicit processes was greatest in the Strategy group, and increased with rotation size in the No-Strategy group. Explicit contributions also remained consistent over Blocks, as well as when re-tested following a 5-minute break. Thus, the results of the current experiment indicate that there are notable differences in explicit and implicit contributions to visuomotor distortions

depending on if, and how participants become aware of the perturbation. The results also highlight the importance of instructions when evaluating reaching performance in aftereffect trials, as they can modulate reaching errors observed.

Chapter I: Literature Review

1. General Introduction

Humans interact with a constantly changing environment. Thus, in order to carry out goal directed movements, we must continually update (or adapt) our movements to meet changes arising in the environment. Motor adaptation is a form of motor learning, which can be defined as the process of acquiring, or restoring previously learned movements to meet a changing environment (Izawa, Rane, Donchin, & Shadmehr, 2008). Many researchers have studied motor adaptation in the laboratory by having participants reach in a virtual reality environment (Baddeley, Ingram, & Miall, 2003; Cheng & Sabes, 2007; van Beers, Wolpert, & Haggard, 2002). Specifically, participants are instructed to reach to a target when visual feedback of their hand's reach trajectory is manipulated from their actual reach trajectory in the form of a cursor on a screen. In general, results reveal that participants are able to adapt to distorted visual feedback, such that they modify their reach trajectory in order for the cursor to reach the target (Cressman & Henriques, 2009; Krakauer, Ghilardi, & Ghez, 1999; Salomonczyk, Cressman, & Henriques, 2011; van Beers et al, 2002). Moreover, participants continue to make adapted movements when visual feedback of the reach trajectory is removed. These adapted reaches are known as aftereffects and are proposed to reflect visuomotor adaptation (Cressman & Henriques, 2009; McNay & Willingham, 1998; Salomonczyk et al, 2011; van Beers et al, 2002).

It has been suggested that both explicit and implicit processes contribute to visuomotor adaptation, where explicit processes can refer to changes in movements arising due to direct or

indirectly acquired strategic processes, as well as implicit processes contribute to changes in movements in the absence of conscious awareness. At present, it is unclear how these two processes contribute to visuomotor adaptation. Moreover, it is unclear if these two processes differ in their contribution depending on the magnitude of the distortion introduced during reach training and hence the magnitude of reach errors experienced by participants, which would influence participants' awareness. The goal of the present experiment was to determine the contribution of implicit and explicit processes to motor adaptation with changes of directly or indirectly acquired awareness.

This literature review first provides an overview of typical paradigms used to study motor adaptation. The focus is on visuomotor adaptation paradigms, which was used in the current experiment. Models are used to explain typical results achieved. Then, results from previous work are discussed in light of the presumed role of explicit and implicit contributions to adaptation. For instance, we compare visuomotor adaptation when the distortion is introduced abruptly, when participants are more likely to become aware of the perturbation indirectly, compared to when the perturbation is introduced gradually, and participants are less likely to be aware of the perturbation. As well, we discuss differences in performance when the distortions differ with respect to magnitude and hence the size of the error experienced (e.g. 30° vs. 70°). Moreover, we discuss how researchers have manipulated explicit awareness directly by looking at the influence of instructions on visuomotor adaptation, and how explicit and implicit processes have been assessed. Finally, we discuss when explicit and implicit processes are proposed to contribute to visuomotor adaptation.

2. Motor adaptation

Goal-directed movements allow us to interact with objects in our environment (Wolpert & Kawato, 1998). In order to carry out a goal-directed movement, the central nervous system transforms sensory information related to the hand and target locations into appropriate motor commands (i.e. to move the hand to the desired location in order to complete the goal-directed movement) (Flanagan et al, 1999; Jeannerod, 1999; Kawato, 1999; Wolpert & Kawato, 1998). The sensory information used to complete these movements is primarily visual (seen hand position) and proprioceptive (felt hand position) in nature.

2.1 Internal Model

A theoretical framework known as the internal model, first proposed by Francis and Wonham (1976), provides insight into the sensory transformations underlying goal-directed movements. The internal model consists of two components: an inverse model and a forward model. The inverse model determines the motor commands required to move the limb from its current position to the desired location based on incoming visual and proprioceptive input and the forward model uses the current motor command and limb position to predict the sensory consequences of the movement (Wolpert, Ghahramani, & Jordan, 1995; Wolpert & Kawato, 1998). More specifically, the forward model, by predicting the sensory outcome of the motor command, produces an internal copy (or efference copy) of the motor command (Jeannerod, 1999; Desmurget & Grafton, 2000; Miall & Wolpert, 1996). The efference copy alerts the sensorimotor system to potential upcoming feedback, which can then use this information to modify the movement if it is predicted that the desired outcome will not be achieved (Sperry,

1950). As well, predicted and actual sensory feedback can be compared both during and following a movement (Desmurget & Grafton, 2000; Miall & Wolpert, 1996). If a difference is detected between the predicted and actual position (i.e. error), the motor command, and hence inverse model, will be updated, as well as the resulting forward model and efference copy (Festinger & Canon, 1965; Kelso, 1977; Sperry, 1950).

Motor adaptation studies have manipulated sensory inputs in laboratory settings to understand how the motor system adapts and internal models are updated. For example, studies have altered one's visual representation of their reach trajectory, so that it differs from where they feel their hand. As such, the brain has to determine how to deal with this conflicting sensory input, which does not match the expected sensory input (Cohen, 1999; Redding & Wallace, 1993, 1994, 1996, 2006; Sainburg & Wang, 2002; van Beers et al, 2002). When the "felt" reach trajectory and seen reach trajectory differ, visual cues tend to override the "felt" reach trajectory, such that movement corrections are based on visual feedback and not proprioceptive feedback. Specifically, participants will alter their reach trajectory according to the visual error experienced as discussed in more detail below (Fine & Thoroughman, 2007; Smith, Ghazizadeh, & Shadmehr, 2006; Tanaka, Sejnowski, & Krakauer, 2009; Tseng, Diedrichsen, Krakauer, Shadmehr, & Bastian, 2007).

3. Sensorimotor Adaptation

In general, three paradigms have been used to study sensorimotor adaptation. Within these paradigms sensory feedback is modified by having participants reach (1) in a velocity dependent force-field, (2) while wearing laterally displacing prism goggles, and (3) in a virtual

reality environment in which the reach trajectory of the hand is misrepresented. Overall, these different paradigms have similar designs, which typically include three phases of testing: (1) a baseline phase, which is used to assess reaching performance prior to a perturbation being introduced, (2) an adaptation phase, in which the perturbation is introduced and participants complete reach training trials, and (3) a post-test, in which the perturbation is removed (Pine, Krakauer, Gordon, & Ghez, 1996; Redding & Wallace, 1993, 1994, 1996; Shadmehr & Mussa-Ivaldi, 1994; van Beers et al, 2002). During the adaptation phase, participants adjust their reaching movement such that initial movement errors are corrected to account for the distorted sensory feedback experienced (Krakauer et al, 1999; Mazzoni & Krakauer, 2006). In general, these movement adjustments have been shown to arise quickly (e.g. within approximately 20 trials), (Krakauer, 2009; Mazzoni & Krakauer, 2006; Salomonczyk et al, 2011; Zbib, Henriques, & Cressman, 2016). In the post-test, participants continue to make persistent deviations in their reaches such that movements differ from the baseline performance and the movement error is in the opposite direction of the perturbation; this behavioural outcome is known as aftereffects (Baraduc & Wolpert, 2002; Buch, Young, & Contreras-Vidal, 2003; Della-Maggiore & McIntosh, 2004; Gandolfo, Mussa-Ivaldi, & Bizzi, 1996; Krakauer et al, 1999; Morris et al, 2004; Scheidt, Reinkensmeyer, Conditt, Rymer, & Mussa-Ivaldi, 2000; Thoroughman & Shadmehr, 2000). Below, we provide a very brief summary of the three paradigms that can be used to assess sensorimotor adaptation.

3.1 Force Field Adaptation

In order to examine how participants adapt the dynamics of their movements, experimenters have participants reach within a force field, which alters the hand's reach

trajectory during the reach but does not alter the end point target (Mattar, Nasir, Darainy, & Ostry, 2011; Shadmehr & Mussa-Ivaldi, 1994). Force fields are typically dependent on velocity, such that the force pushes the hand either left or right depending on movement velocity. Thus, participants have to modify their movement torque to push against the force field in order to land on the target. Specifically, participants counteract a right force field by pushing in the leftward direction in order to land on the target (Shadmehr & Mussa-Ivaldi, 1994; Sing, Joiner, Nanayakkara, Brayanov, & Smith, 2009). Once the force field is removed, participants demonstrate aftereffects such that they continue to make “pushing” movements in the opposite direction of the force field, so their reach trajectory is curved away from the target as though the force field was still present (Brown, Wilson, Goodale, & Gribble, 2007; Cashaback, McGregor, & Gribble, 2015; Malfait & Ostry, 2004; Mattar et al, 2011; Shadmehr & Mussa-Ivaldi, 1994; Sing et al, 2009).

3.2 Prism Adaptation

In prism adaptation paradigms, participants wear laterally displacing prism while pointing at a target in the adaptation phase of the experiment (Harris, 1963; Rossetti, Koga, & Mano, 1993; Von Helmholtz, 1962; Weiner, Hallet, & Funkenstein, 1983; Welch, Bridgeman, Anand, & Browman, 1993). When wearing the prism goggles, the entire environment is shifted to the left or right (e.g. a deviation of 10° to the right), and as a result, movement kinematics must be altered to land on the target (Harris, 1963; Held, 1965; Redding & Wallace, 1993, 1994, 1996, 2002, 2003, 2006; Von Helmholtz, 1909/1962). In the first experiment to use this paradigm, Von Helmholtz (1909/1962) found that errors gradually decreased during repeated reaches with the prisms, and after the removal of the prisms, participants reached in the

opposite direction of the prism shift. Specifically, Harris (1963) found that following reach training with prisms that displaced the visual field by approximately 12 cm to the left or right, participants would reach 6 cm in the opposite direction of the distortion, (i.e. if the prisms displaced the visual field to the left, after removing the prisms, the participant would reach towards the right). Thus, aftereffects were approximately 50% of the magnitude of the distortion. Similarly, Pisella and colleagues (2004) found that participants who trained with prism goggles that produced a shift of approximately 15° to the left had aftereffects of 6.5° to the right, corresponding to nearly 43% of the distortion. The aftereffects observed following reaches with prisms are proposed to reflect implicit changes in the motor system, as participants are aware that they are again reaching in a normal environment and not wearing prism goggles (Pisella et al, 2004; Redding & Wallace, 1993, 1994; Rossetti et al, 1993).

3.3 Visuomotor Adaptation

In the two previous paradigms, participants are aware of the distortion being introduced (e.g. their hand being pushed off course or putting on prism goggles). In the third paradigm, visuomotor adaptation is examined by having participants reach to a target when visual feedback of their reach trajectory is manipulated from their actual reach trajectory in the form of a cursor on a screen. In this paradigm, participants may or may not be aware of the distortion depending on how the cursor perturbation is introduced. Typically, the cursor feedback is either translated (left or right) or rotated clockwise (CW) or counter clockwise (CCW) with respect to the hand (Ghahramani & Wolpert, 1997; Mazzoni & Wexler, 2009; Thomas & Bock, 2012; Wang & Sainburg, 2003; Woolley, Tresilian, Carson, & Riek, 2007). If a participant reaches, for example, towards a centre target and misses the target, on the

following trial, the participant will adjust their movement to counteract the visual shift or rotation of the cursor (altered visual feedback) in attempt to aim the cursor to the target (Abeele & Bock, 2001; Cressman & Henriques, 2009; Krakauer, 2009; Mazzoni & Krakauer, 2006; Sainburg & Wang, 2002). These adapted movements persist even when the cursor is removed in the post-test, and as with the other adaptation studies discussed above, are in the opposite direction of the distortion (Krakauer, 2009; Mazzoni & Krakauer, 2006; van Beers et al, 2002). In general, aftereffects have been shown to correspond to approximately 60% of the distortion (Cressman & Henriques, 2009; Salomonczyk et al, 2011), which is comparable in magnitude with what has been previously found in prism adaptation literature (Harris, 1963; Pisella et al, 2004).

3.4 Motor Adaptation and Model-Free Processes

Motor adaptation in the form of aftereffects has been suggested to arise due to error-based processes, as explained by the internal model framework described above (see section 2.1 Internal Model; Miall & Wolpert, 1996; Tseng et al, 2007; Wei & Kording, 2008). Recently, other processes have also been suggested to contribute to motor adaptation, specifically visuomotor adaptation. These processes, which are not accounted for by the internal model include use-dependent plasticity, operant conditioning and explicit knowledge (Huang, Haith, Mazzoni, & Krakauer, 2011). Use-dependency has been shown to produce directional biases that occur from repeated movements to the same designated region of the workspace (Diedrichsen, White, Newman, & Lally, 2010; Verstynen & Sabes, 2011). Operant conditioning, through reward or punishment, has also been shown to influence visuomotor adaptation (Galea, Mallia, Rothwell, & Diedrichsen, 2015; Huang et al, 2011; Izawa & Shadmehr, 2011;

McDougle et al, 2016). As well, explicit knowledge has been suggested to influence visuomotor adaptation as discussed below (Benson, Anguera, & Seidler, 2011; Taylor & Ivry, 2011; Willingham, Salidis, & Gabrieli, 2002).

4. Manipulating Awareness During Visuomotor Adaption Studies

4.1 How Indirect Awareness Can Be Acquired in Visuomotor Adaptation Studies

Explicit knowledge can be obtained indirectly by the participant (i.e. without direct intervention of the researcher) by simply interacting with a task. When a participant interacts with a task, they can develop their own strategies, but only when they are conscious of the error they are making. This acquired knowledge regarding the change in the reaching environment (and potentially of the perturbation itself) and how to counteract it, is dependent on how a perturbation is introduced and the magnitude of the perturbation, which alter the magnitude of the errors experienced (Hwang, Smith, & Shadmehr, 2006; Redding & Wallace, 1996; Taylor, Krakauer, & Ivry, 2014; Werner et al, 2015).

Typically, participants show larger errors during reach training trials when the perturbation is introduced abruptly compared to gradually. This has been shown by Kagerer and colleagues (1997), who used a visuomotor adaptation task and had participants adapt to either an abruptly introduced 90° counter clockwise (CCW) rotation or a 90° CCW rotation that was introduced gradually in increments of 10° until the rotation achieved 90°. The abrupt 90° CCW perturbation resulted in participants initially making significant errors corresponding to nearly 50% of the perturbation magnitude. Over the course of training, reach trajectory errors gradually decreased so that the cursor achieved the target. Alternatively, participants training

with the gradually introduced perturbation showed little error in their reaching training movements to a target and performance remained similar to their baseline performance (i.e., without a rotation). The participants who were assigned a gradually introduced perturbation were found to reach faster and had greater aftereffects compared to participants adapting to the abrupt perturbation. These results are in agreement with other studies that have manipulated how the distortion was introduced during adaptation trials (gradually or abruptly) (Galea, Sami, Albert, & Miall, 2010; Kagerer, Contreras-Vidal, Bo, & Clark, 2006; Werner, Schorn, Bock, Theysohn, & Timmann, 2014). Differences arising depending on how the distortion is introduced, may have to do with participants' level of awareness of the misaligned visual feedback and the resulting contribution of implicit processes to visuomotor adaptation. In an abruptly introduced perturbation, there is a larger error between the cursor and target at the beginning of training, which could contribute to a participant become aware of the perturbation indirectly. However, a gradually introduced perturbation would lead to a small reaching error, leaving the participant potentially unaware of the perturbation and hence leading to greater implicit processes giving rise to visuomotor adaptation.

Another method for manipulating potential awareness of the perturbation indirectly is by changing the magnitude of the distortion introduced. Visuomotor adaptation studies have used distortions of various magnitudes, ranging from small distortions (e.g. 15° rotation) to large distortions (e.g. up to 90° rotation) (Abeele & Bock, 2001, 2003; Bond & Taylor, 2015; Hegele & Heuer, 2010; Kagerer et al, 1997; Thomas & Bock, 2012; Werner et al, 2015). In early training, during the first few adaptation trials, greater directional errors are typically seen with larger distortion angles compared to smaller distortion angles. However, by the end of

adaptation, training with a smaller or larger distortion becomes comparable, such that participants tend to reach to the target (Bond & Taylor, 2015; Thomas & Bock, 2012; Werner et al, 2015). With a small rotation size, participants tend to show greater aftereffects when reach errors are expressed as a percentage of the distortion introduced. For example, in an experiment by Werner et al (2015), there was a trend of greater aftereffects for participants after training with a 20° CW rotation compared to a 40° or 60° CW rotation. These larger aftereffects were accompanied by less error at the beginning of reach training trials. However, by the end of the adaptation phase, participants adapted their movements to the rotation in a similar manner regardless of the perturbation size. Bond & Taylor (2015) have also shown that training with smaller rotations leads to significantly greater aftereffects as expressed as a percentage of the distortion introduced compared to larger rotations (e.g. 15° or 30° compared to 60° or 90°). Again, the different patterns in performance between reach training trials and aftereffect trials when the magnitude of the distortion was manipulated can be explained by a participant's awareness. As such, it has been proposed that since participants are more likely to become aware of the perturbation indirectly when it is large (e.g. greater than 60° CW), they are able to develop a strategy to counteract the rotation (Werner et al, 2015). This use of a strategy or awareness results in less implicit processes contributing to visuomotor adaptation and hence smaller aftereffects.

4.2 Direct Strategy Use in Visuomotor Adaptation Studies

Explicit knowledge can also be manipulated more directly by providing participants with instructions regarding the perturbation and how to counteract it (Benson et al, 2011; Mazzoni & Krakauer, 2006; Taylor & Ivry, 2011). In accordance with the results discussed above,

knowledge in visuomotor adaptation tasks has previously been shown to lead to performance benefits compared to performance in the absence of strategies or awareness, such that participants make less errors during reach training trials and hence are more accurate (McDougle, Bond, & Taylor, 2015; Redding & Wallace, 1996; Taylor et al, 2014; Weiner et al, 1983; Werner et al, 2015). As well, participants adapt to a perturbation faster when provided with explicit knowledge of the perturbation (Benson et al, 2011; Werner et al, 2015). However, participants tend to demonstrate less aftereffects with explicit knowledge (Benson et al, 2011; Mazzoni & Krakauer, 2006; Werner et al, 2015).

The experiment conducted by Mazzoni and Krakauer (2006) was one of the first to manipulate awareness directly with the use of instructions. Specifically, they informed participants that there would be a 45° CCW rotation introduced and instructed them on how to counteract it (i.e. participants instructed to aim towards the CW neighbouring target). Likewise, Benson et al (2011) provided participants in an explicit group with instructions of how to counteract their perturbation. Participants were presented with the image of a clock face and the researchers explained how to counteract a 30° rotation by using the numbers on the clock face. For example, participants were instructed that reaching towards the 12 on the clock would result in the cursor moving towards the 1 position. Therefore, participants were instructed to reach towards the 11, for the cursor to reach the assigned target at the 12 position. This was explained for each of the four target locations and participants drew on the clock face to confirm they understood the instructions they received. As mentioned above, participants in their explicit groups showed more accurate performance in early adaptation. However, in general, the explicit group was less precise as indicated by greater variability in

reaching during the first 40 trials with the distorted visual feedback. In addition, the explicit group also showed less aftereffects compared to the implicit group that was not provided with instructions.

Taken together, the above results show that there is an obvious performance advantage for participants who are aware of a perturbation during adaptation training, where participants' awareness can be manipulated indirectly, by changing how a perturbation is introduced (abruptly vs. gradually) or the magnitude of the distortion, or directly, by the experimenter providing a strategy. Specifically, performance is more accurate when participants are aware of the perturbation as explicit processes play a greater role compared to when participants are unaware. However, this advantage of awareness during adaptation training does not appear to extend to aftereffects. This provides support to the notion that aftereffects in visuomotor adaptation reflect implicit processes and arise without awareness.

4.3 Assessments of Explicit Knowledge

Explicit awareness has typically been probed by post-experiment questionnaires (Benson et al, 2011; Heuer & Hegele, 2008; Hwang et al, 2006; Werner et al, 2015). For example, participants are asked if they noticed a change in the task immediately after the experiment is completed (i.e. indicate that the task is more difficult when the perturbation is present than baseline trials). Participants are then further probed on the perturbation itself. If they are able to indicate and describe (or draw) how the cursor movement did not correspond with the intended cursor trajectory, they are classified as being "aware" of the perturbation (Benson et al, 2011; Heuer & Hegele, 2008; Hwang et al, 2006; Werner et al, 2015). Recently,

Taylor, Krakauer, and Ivry (2014) have come up with a new method to measure awareness. In their task, participants are instructed to verbally report the location they plan to aim to in order for the cursor to hit the target by using visual landmarks provided. This reporting is done on a trial-by-trial basis during the adaptation trials. This method assumes that explicit and implicit contributions can be isolated and their sum represents the amount of visuomotor adaptation achieved.

Building on this idea that implicit and explicit processes contribute to the amount of visuomotor adaptation in a linear manner, Werner and colleagues (2015) have introduced the notion of using a process dissociation procedure (PDP) to assess awareness. This method looks at the contribution of awareness to performance in the post-test (i.e. when aftereffect trials are typically completed), which up to this point have been assumed to reflect implicit processes. In this method, participants are instructed to use the behaviour they learned during the reach training trials (“use the strategies that you have developed from what was learned during training”) or to repress the learned behaviour (“do not use any strategies, aim to the target as you would have during baseline”) in a series of reaches with no visual feedback. Combining the PDP and traditional post-experiment interviews/questionnaires to assess awareness, Werner and colleagues (2015) showed that PDP provides a better measure of awareness, as post-experiment interviews underestimate awareness. As well, they have demonstrated that explicit instructions provided in the post-test are critical to avoid explicit knowledge potentially contributing to performance.

5. Modeling Explicit and Implicit Contributions to Motor Adaptation

Redding and Wallace (1996) were one of the first to propose that two distinct adaptive processes give rise to prism adaptation, which they termed strategic perceptual-motor control and adaptive spatial alignment (Redding & Wallace, 2001). The first process was proposed to arise consciously (or with awareness), while the second process arose implicitly. Specifically, when participants first noticed they had missed the target, they would consciously alter their movement. Thus, a participant would reach in the opposite direction of the visual feedback provided. Therefore, this conscious process allowed for a quick initial reduction in movement errors when reaching with altered visual feedback of the hand (Newport & Schenk, 2012). In parallel, visual and proprioceptive maps were implicitly realigned to reduce movement error, This realignment persists throughout adaptation by gradually and constantly reducing movement error (Newport & Schenk, 2012).

Recently, a model, put forward by Smith and colleagues (2006), proposed a two-state model of adaptation by using results obtained from force field adaptation studies. Their two states are similar to the stages proposed by Redding and Wallace (1993, 2001), in that there is a fast and a slow process operating in parallel. The fast process is proposed to contribute to adaptation quickly by reducing initial direction error. Whereas, the slow process, allows participants to slowly and gradually reduce their movement error. This model has also been shown to accurately predict adaptation patterns achieved in visuomotor adaptation paradigms (McDougle et al, 2015; Taylor et al, 2014; Trewartha, Garcia, Wolpert, & Flanagan, 2014; Werner et al, 2015). Moreover, the fast process has been suggested to reflect explicit processes, by showing a quick reduction in initial movement direction error along with a fast

decay, whereas the slow process has been suggested to reflect implicit processes (Trewartha et al, 2014).

Support for explicit and implicit processes operating in parallel can be seen in visuomotor adaptation studies with older participants. In general, in both early and late adaptation training, younger participants show more accurate performance when reaching with a perturbation compared to older participants, thus suggesting that adaptation to a visuomotor rotation declines with age (Bock, 2005; Bock & Girgenrath, 2006; Buch et al, 2003; Hegele & Heuer, 2013; Heuer & Hegele, 2008; McNay & Willingham, 1998). However, it is noteworthy to mention that aftereffects are similar for older participants and younger participants. Based on these results, it has been suggested that decreases observed in performance when exposed to a perturbation arise due to declines in the ability to use explicit knowledge, whereas the maintenance of aftereffects reflects intact implicit processing.

The current models, as discussed above, would predict that the unconscious process (i.e. adaptive spatial realignment, the slow process or implicit processes) remains consistent and stable over time during aftereffects trials. However, recent literature contradicts this prediction. Specifically, it has been shown that suggest that (implicit) reach errors decrease gradually within aftereffects trials (Taylor et al 2014; McDougale et al 2015). Although, it is important to note that the results of these experiments would indicate there may be a quick decay of implicit processes during aftereffects trials (e.g. Zbib et al. (2016)) show within 5 minutes), this is only a speculation as implicit contribution to aftereffect trials has not been analyzed directly or over time.

Specific Objectives

As discussed in this literature review, it is evident that both explicit and implicit processes contribute to motor adaptation. However, what is not yet clear, is if these two processes contribute differently depending on participants being made aware of the distortion directly or indirectly. Moreover, it is unclear when these two processes start to contribute to visuomotor adaptation. This experiment sought to answer the following questions: Do the contributions of explicit and implicit processes to visuomotor adaptation change with direct versus indirect awareness, and do these contributions change over time? To answer these questions, we made half of our participants directly aware of the perturbation by providing them with a strategy and compared their performance to a no strategy group (Benson et al, 2011; Mazzoni & Krakauer, 2006). Furthermore, similar to the experiment by Werner et al (2015), we manipulated the size of the distortions (20°, 40°, or 60°) that participants reached with to manipulate awareness indirectly. To assess explicit and implicit contributions to visuomotor adaptation over time, participants completed two sets of reaches without visual feedback within the PDP framework at four different time points during reach training trials. The first set of reaches without visual feedback were completed immediately following a block of reach training trials and a second time after a 5-minute rest, as reach adaptation has been suggested to decay rapidly (Taylor et al, 2014; Zbib et al, 2016). We also provided participants with a post-experiment questionnaire to assess awareness at the end of the experimental testing session.

We hypothesized that explicit processes had a greater contribution to visuomotor adaptation for participants provided with instructions on the perturbation, when awareness

was provided directly, compared to participants in the No-Strategy group. Moreover, we expected a greater contribution of explicit processes with the larger distortion, regardless of which group participants were assigned to, as participants were more likely to become aware of the distortion indirectly. In contrast, implicit processes may have contributed more to visuomotor adaptation for the participants who trained with the smaller distortion, regardless of if they were made aware of the distortion directly or became aware indirectly. Finally, it was hypothesized that the post-experiment questionnaire will underestimate awareness compared to the PDP, but that awareness as determined by the questionnaire would be related to the explicit index provided by the PDP.

Chapter II: Research Article

The Influence of Awareness on Explicit and Implicit Contributions to Visuomotor Adaptation to Different Rotation Sizes

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Abstract

Explicit (strategic) and implicit (unconscious) processes play a role in visuomotor adaptation (Bond & Taylor 2015; Werner et al. 2015). We investigated the contributions of explicit and implicit processes to visuomotor adaptation when awareness was manipulated directly versus indirectly, and ask how these contributions change over time. Participants were assigned to a Strategy or No-Strategy group. Those in the Strategy group were made aware of the visuomotor distortion directly. Participants were further subdivided into groups to train with a large (60°), medium (40°) or small (20°) visuomotor distortion, providing the potential for awareness to develop indirectly. Participants reached with their respective distorted cursor, followed by a series of no-cursor reaches to assess the contributions of explicit and implicit processes to visuomotor adaptation after every 30 reach training trials. Within the no-cursor reaching trials, participants reached (i) with any strategies they had gained during training (explicit + implicit processes), and (ii) as accurately to the target as possible (implicit processes). Results showed that implicit contributions to visuomotor adaptation were greatest in the No-Strategy group and took time to develop. Explicit processes were greatest in the Strategy group, increased with rotation size in the No-Strategy group, and remained consistent over time. Taken together, results reveal that there are notable differences in explicit and implicit contributions to visuomotor distortions depending on if, and how participants become aware of the perturbation. Moreover, the results highlight the importance of instructions when evaluating reaching performance in no-cursor trials, as they can modulate reaching errors.

1. Introduction

In order to carry out goal directed movements, the central nervous system needs to transform sensory information related to hand and target locations into appropriate motor commands for the environment in which one is reaching (Flanagan et al, 1999; Jeannerod, 1999; Kawato, 1999; Wolpert & Kawato, 1998). The sensory information used to plan and execute reaching movements is primarily visual and proprioceptive in nature. In general, these two sensory modalities are aligned, such that the position one sees their hand is the same as the position at which they feel their hand. However, situations can arise in which these signals differ and the visual and proprioceptive signals conflict (e.g. reaching to an object under water). When sensory signals conflict, humans tend to rely on the visual estimate of hand location as opposed to the “felt” or actual position (Fine & Thoroughman, 2007; Mazzoni & Krakauer, 2006; Redding & Wallace, 1993, 1996, 2001; Smith et al, 2006; Tanaka et al, 2009; Tseng et al, 2007). Thus, movements are corrected based on the visual estimate of the hand.

Evidence for this reliance on visual information can be seen from results arising from visuomotor adaptation paradigms in the lab. In these paradigms, participants train to reach to a visual target while seeing a cursor that is misaligned from their actual hand position (i.e. the cursor is rotated or translated relative to the hand). Initially, participants’ movements are deviated such that the cursor deviates from the target direction. However, participants rapidly adapt their movements so that the cursor will successfully land on the target (Cressman & Henriques, 2009; Fine & Thoroughman, 2007; Krakauer, Ghilardi, & Ghez, 1999; Krakauer, Pine, Ghilardi, & Ghez, 2000; Sainburg & Wang, 2002; Simani, McGuire, & Sabes, 2007; Smith et al, 2006; Tanaka et al, 2009; Tseng et al, 2007; Zbib, Henriques, & Cressman, 2016). Furthermore,

when participants reach in the absence of visual feedback, they demonstrate persistent movement deviations in the opposite direction of the visual distortion experienced. For example, if the cursor was rotated clockwise (CW) relative to the hand, participants reach counterclockwise (CCW) relative to the target. These deviations reflect persistent changes in the motor system and are referred to as reach aftereffects (Baraduc & Wolpert, 2002; Buch, Young, & Contreras-Vidal, 2003; Cressman & Henriques, 2009; McNay & Willingham, 1998; Morris et al, 2004; Salomonczyk, Cressman, & Henriques, 2011; Scheidt, Reinkensmeyer, Conditt, Rymer, & Mussa-Ivaldi, 2000; Thoroughman & Shadmehr, 2000; van Beers, Wolpert, & Haggard, 2002).

Explicit knowledge of the novel visuomotor environment in which one is reaching has been shown to influence performance while training with a visuomotor distortion and resulting aftereffects, where explicit knowledge has been manipulated indirectly by varying the magnitude of the distortion presented (e.g. rotation size), or directly by providing participants with explicit knowledge and hence a strategy to counter the rotation during the reach training phase. The distortion can be manipulated by varying how it is introduced (i.e. gradually vs. abruptly) and/or by presenting large (e.g. 60° rotation) versus small (e.g. 15° rotation) distortions. In general, larger distortions experienced lead to participants becoming aware of the distortion (Malfait & Ostry, 2004), as they initially experience larger errors in reaching (i.e. are farther away from the target) compared to when reaching with a small distortion or with a gradually introduced distortion. This knowledge has been shown to lead to participants correcting their movements in fewer trials compared to participants without knowledge of the perturbation (i.e. faster visuomotor adaptation during reach training trials)(Benson et al, 2011).

However, by the end of the reach training trials with misaligned visual feedback, the extent of visuomotor adaptation tends to be comparable across participants, regardless of the initial distortion size (i.e. all participants can successfully achieve their target, regardless of initial rotation size (Bond & Taylor, 2015; Thomas & Bock, 2012; Werner et al, 2015)). Explicit knowledge can also be manipulated directly by providing participants with instructions regarding the perturbation and how to counteract it (Benson et al, 2011; Mazzoni & Krakauer, 2006; Taylor & Ivry, 2011). For example, in an experiment by Benson et al (2011), participants were presented with the image of a clock face and the researchers explained how to counteract a 30° rotation by using the numbers on the clock face (e.g. participants were instructed to reach towards the 11 in order for the cursor to land on the assigned target at the 12 position). In accordance with the results discussed above, providing knowledge of a visuomotor distortion has been shown to lead to faster visuomotor adaptation during reach training trials compared to when participants are unaware of the perturbation (Benson et al, 2011; Werner et al, 2015).

The relationship between explicit knowledge and aftereffects is less clear. Traditionally, aftereffects have been assumed to reflect implicit processes/learning engaged during visuomotor adaptation training with misaligned visual feedback of the hand (Benson et al, 2011; Mazzoni & Krakauer, 2006; Redding & Wallace, 1996; Smith et al, 2006; Willingham, Salidis, & Gabrieli, 2002), as participants reach in the absence of visual feedback with the goal of attaining the target. A number of studies have shown larger aftereffects in participants with less awareness of the perturbation (Galea, Sami, Albert, & Miall, 2010; Kagerer, Contreras-Vidal, Bo, & Clark, 2006; Werner et al, 2015; Werner, Schorn, Bock, Theysohn, & Timmann, 2014), leading to the proposal that the use of a strategy or greater awareness during reach

training results in less engagement of implicit processes during reach training and hence smaller aftereffects (Abeele & Bock, 2001). These findings were recently corroborated by Bond and Taylor (2015), who showed that implicit processes, as reflected in aftereffects trials, were less when expressed as a percentage of the distortion introduced for the larger compared to the smaller distortions. In fact, they showed that implicit contributions to visuomotor adaptation achieved a maximum level overall of 8°-12°, regardless of the size of the distortion that participants trained with (15°, 30°, 60° or 90°).

In contrast to these results, Werner and colleagues (2015), recently showed that implicit contributions to visuomotor adaptation did not vary with direct awareness of the perturbation using their Process Dissociation Procedure (PDP). Within their experimental design, participants first completed reach training trials with a cursor that was rotated relative to the hand by 20°, 40° or 60°. Half of the participants were made aware of the perturbation and instructed on how to counteract the rotated cursor, while the other half of the participants were not made aware of the distortion. All participants then completed the PDP trials, in which they were instructed to use the behaviour they had learned during the reach training trials (“use the strategies that you have developed from what was learned during training”) or to repress the learned behaviour (“do not use any strategies, aim to the target as you would have during baseline”), while they reached to targets in the absence of visual feedback of their hand position (i.e. aftereffect trials with specific instructions provided). The first set of trials, in which participants were to reach using any strategy they picked up during training, was assumed to reflect explicit + implicit processes, whereas the second set of trials was assumed to reflect implicit processes. Results revealed that explicit and implicit processes differed in their contribution to visuomotor

adaptation, depending on participants' level of awareness of the perturbation. Specifically, they found that participants who were made aware of the distortion and/or reached with a greater rotation size, showed greater explicit contribution to visuomotor adaptation compared to participants who were not made aware of the distortion. In contrast, there was no difference in implicit contributions to visuomotor adaptation between participants who were provided with a strategy versus those participants who were not provided with a strategy.

From previous work, it is evident that both explicit and implicit processes contribute to visuomotor adaptation. These processes appear to be modulated by participants' level of awareness of the novel visuomotor environment that they are reaching in and can be evaluated during sets of PDP aftereffect trials. However, what is not yet clear, is if these two processes contribute differently depending on participants' level of awareness, and whether this awareness is achieved directly or indirectly. Moreover, it is unclear when explicit and implicit processes begin to contribute to visuomotor adaptation as assessed through PDP trials. The current experiment therefore looked to address the following questions: Does awareness achieved both directly and indirectly influence the contributions of explicit and implicit processes to visuomotor adaptation, and do these contributions change over time? To answer these questions, we compared performance in a PDP framework across participants who were provided with a strategy regarding the visuomotor distortion, like in Benson and colleagues' experiment (2011), to a No-Strategy group. Furthermore, we manipulated awareness indirectly by changing the magnitude of the distortion experienced by introducing participants to one of three different distortion sizes (20°, 40°, or 60°). To assess explicit and implicit contributions to visuomotor adaptation over time, participants completed two sets of reaches without visual

feedback within the PDP framework at four different time points during reach training trials. The first set of trials was completed immediately following a block of 30 reach training trials and a second time after a 5-minute rest, as visuomotor adaptation has been shown to decay rapidly (Taylor et al, 2014; Zbib et al, 2016). We also provided participants with a post-experiment questionnaire to assess awareness at the end of the experimental testing session. We hypothesized that explicit processes would have a greater contribution to visuomotor adaptation for participants provided with instructions on the perturbation, when awareness was provided directly, compared to participants in the No-Strategy group. Moreover, we expected a greater contribution of explicit processes with the larger distortion, regardless of which group participants were in, as participants were more likely to become aware of the distortion indirectly. In contrast, implicit processes were expected to contribute more to visuomotor adaptation for the participants training with the smallest distortion, regardless if they were made aware of the distortion directly or became aware indirectly.

2. Methods

2.1 Participants

Sixty-three participants (27 males), aged 18-27 years old ($M = 22$, $SD = 2.62$), were recruited from the University of Ottawa community. Participants were naïve to the purpose of the experiment and had no previous experience with the task. Prior to beginning testing, all participants were confirmed to be right-handed by the Edinburgh Handedness Inventory ($M = 76.42$, $SD = 24.37$) (Oldfield, 1971). In addition, participants self-reported to have normal or corrected-to-normal vision, and no neurological, sensory or motor dysfunction. All participants

provided informed consent and the experiment was approved by the University of Ottawa Research Ethics Board. Each participant completed testing in one session, which lasted approximately 70 minutes. Following testing, one participant's set of data from the Strategy Group was excluded from analyses due to the participant reporting that they stopped following instructions part way through the experiment.

2.2 Apparatus

Participants were seated in front of the experimental apparatus. They were instructed to adjust the height and distance of chair to ensure they were seated comfortably and could reach to all possible target locations during the testing session (Figure 1A). Participants were asked to firmly grip a vertical handle of a two-joint robot manipulandum (BKIN technologies; Kingston, Canada) with their right hand. They were then required to make reaching movements to three visual targets within a 70 cm by 36 cm workspace (Figure 1B). The targets were projected onto a horizontal reflective surface from a downward facing computer monitor (EzSign model 47LD452B; refresh rate: 60Hz; LG, Seoul, South Korea), that was placed 20.5 cm above the reflective surface. The robot manipulandum was 20.5 cm below the reflective surface, so that the visual stimuli appeared to lie in the same plane as the reaching hand. When they were ready to begin testing, participants positioned their hand, as represented by a visual cursor (green circle, 1 cm in diameter), at the home position. The home position was represented by a white circle, 1 cm in diameter, at the midline of the body of each participant, approximately 20 cm in front of the participant's chest. The three visual targets, represented by yellow circles, 2 cm in diameter, appeared 15 cm from the home position at positions corresponding to straight ahead, 40° clockwise (CW) and 40° counter-clockwise (CCW) relative

to straight ahead. A participant's hand was hidden from view by a black cover placed between his or her shoulders and apparatus, with the light in the room turned off.

2.3 Experimental Procedure

Participants were pseudo-randomly assigned to one of six subgroups. Specifically, half of the participants were assigned to the Strategy and No-Strategy groups ($n = 32$ and $n = 31$ in each group, respectively). These groups were then further subdivided into three smaller groups that trained with a cursor that was rotated 20° , 40° or 60° CW relative to the hand (for clarification of the breakdown of the participants into groups, see Figure 2). Once a participant verbally confirmed that they were seated comfortably, the experimenter briefly explained the tasks that would be completed during the testing session. All participants completed four testing Blocks within the testing session (Figure 1C). Within each testing Block, there was 1 set of 30 reach training trials followed by 36 Process Dissociation Procedure (PDP) trials. In the first block, the 30 reach training trials were completed with the cursor accurately representing the participant's hand position (i.e. the cursor was aligned with his or her actual hand position). In the remaining 3 blocks (Blocks 2 – 4), the reach training trials were completed with misaligned visual feedback such that the cursor representing the hand was rotated by 20° , 40° or 60° CW relative to the hand's motion depending on the group the participant was assigned to. Therefore, participants completed 120 reach training trials in total and 144 PDP trials. Finally, the experiment concluded with participants completing a post-experiment questionnaire, as used by Benson et al (2011) (see Figure 3), to measure their awareness of the distortion.

2.3.1 REACH TRAINING TRIALS

Participants were instructed to reach to one of three visual targets as quickly and accurately as possible while grasping the vertical robot handle with a firm, but comfortable grip. The hand, as represented by the cursor, started at the home position and was maintained at this position for 500 ms, after which one of the three visual targets appeared with equal probability. Once the target appeared, the home position disappeared and was not shown again during the rest of the reach training trials. The cursor feedback appeared once the hand had moved 7 cm from the home position, which corresponded with the point where participants generally achieved peak velocity. In the first set of reach training trials in Block 1 (baseline set), the cursor was aligned with the actual position of the participant's hand. Thus, if the participant moved his or her hand directly to the target, the cursor moved directly to the target as well. During the next three sets of reach training trials (Blocks 2 – 4), the cursor was rotated relative to the hand's actual reach trajectory by either 20°, 40° or 60° CW, depending on the subgroup the participant was assigned to (Figure 1C). During the 30 reach training trials, participants would randomly reach to all three targets 10 times. Upon movement completion, (i.e. when the cursor successfully achieved the target), both the target and cursor disappeared. Participants then moved their hand back to the home position by way of a linear grooved path, such that if they attempted to move outside of the designated path, a resistance force (proportional to the depth of penetration with a stiffness of 2 N/mm and a viscous damping of 5 N/(mm/s)) was produced perpendicular to the grooved wall. The position of the robot handle was recorded at all times at a sampling rate of 1000 Hz and a spatial accuracy of 0.1mm.

2.3.2 STRATEGIES PROVIDED DURING THE REACH TRAINING TRIALS

As mentioned above, participants were assigned to either the Strategy or No-Strategy groups. During a three-minute break before the first set of rotated reach training trials (in Block 2, see Figure 1C), the Strategy group was provided with a strategy on how to counteract the rotation that would be introduced. They were also reminded of this strategy before each subsequent set of reach training trials with the rotated cursor (i.e. in Blocks 3 and 4). Instructions were similar to those provided by Benson et al (2011). Specifically, participants were shown a picture of a modified clock face (see Figure 3). The experimenter then explained the nature of the distortion (i.e. a CW rotation of 20°, 40° or 60°) by using the clock and showing how the distortion should be counteracted at one of the three target locations. For example, participants in the 20° Rotation subgroup were told to aim to the 15 in order for the cursor to achieve the left target (located at 16). The participant then drew on the clock face where they had to reach to in order to counter the rotation for the other two target locations. Once participants could accurately draw on the clock face where they were required to reach to and they verbally confirmed that they understood the task, they began the rotated reach training trials (all participants achieved these criteria after one instruction trial, except for one participant who needed the instructions repeated a second time). During this period, the No-Strategy group was not provided with a strategy regarding the upcoming perturbation. Instead they were instructed to sit quietly for 5 minutes (Figure 1C). Before beginning their sets of reach training trials they were instructed to aim their cursor to the target.

2.3.3 PROCESS DISSOCIATION PROCEDURE (PDP TRIALS)

These trials were used to dissociate explicit and implicit contributions to visuomotor adaptation. Within each Block of trials, participants completed 9 “inclusion” and 9 “exclusion” PDP trials two times, equally distributed across the three targets that randomly appeared (Figure 1C). Similar to Werner and colleagues (2015), in the inclusion trials participants were instructed to “use what you have learned during training trials,” and in the exclusion trials they were instructed to “refrain from using what was learned during training trials, and perform the movements as you were during the baseline”. It is important to note that it assumed that no strategy the exclusion trials. The order in which these inclusion and exclusion trials were completed was counterbalanced across participants. Participants completed 18 trials (9 inclusion + 9 exclusion trials) immediately after each set of reach training trials and then the other 18 trials again after a five-minute rest (Figure 1C). The order of exclusion and inclusion trials was the same before and after the five-minute rest interval, as well as across all Blocks of testing.

All PDP trials were similar to the reach training trials, such that participants were instructed to continue grasping the robot handle with a comfortable, yet firm grip. The hand position was maintained at the home position for 500 ms before a visual target appeared in one of the three target positions. Participants were then instructed to reach as quickly and accurately as possible to the visual target using either what they had learned during training (Inclusion trials) or like they had during the baseline Block (Exclusion trials). However, during this task, no visual feedback (i.e. no cursor) representing the hand was provided. Participants’ reaches were considered complete once they had maintained a final hand position for 1000 ms.

Upon movement completion, the visual target disappeared and the participant moved his or her hand back to the home position by way of the linear grooved path.

2.3.4 POST-EXPERIMENT QUESTIONNAIRE

At the end of the experiment, participants answered a post-experiment questionnaire to assess their awareness of the perturbation and any strategy used to counteract it (see Figure 4). The questionnaire was adopted from Benson et al (2011), and asked questions such as: (1) Did you notice the task get harder at any point?, (2) Do you know why it became harder?, (3) How many degrees (was it rotated) did you push? As done by Benson et al (2011), participants were classified as being aware if they indicated the presence of a perturbation (i.e. had to push their hand left) and described the perturbation (i.e. trained with a 60° CW cursor). Based on their responses, participants were classified as aware or unaware of the distortion. At the end of the questionnaire, participants were debriefed about the nature and purpose of the experiment. In addition, they verbally confirmed the use of their data and were thanked for their participation.

2.4 Data and Statistical Analysis

Reaching performance during all trials was analyzed using custom written programs in MATLAB. First, the start and endpoint of each reaching movement (all Reach Training trials and PDP trials), were defined by using a velocity criterion, such that the start and end of the movement were selected as the points in time when velocity first increased above or decreased below 0.01m/s for 50 ms, respectively. For each of these reaching profiles, we then determined reaction time (RT, movement time (MT) and the angular error at peak velocity (PV), where PV angular error was defined as the angular difference between a movement vector (from the

home position to peak velocity) and a reference vector (joining the home position and the target).

RT and MT were both analyzed for all reach training trials using a 2 Group (Strategy vs. No-Strategy) x 3 Rotation Size (20°, 40° vs. 60°) x 4 Block (Block 1, Block 2, Block 3 vs. Block 4) x 2 Bin (average of first 3 bins vs. average of last 3 bins) mixed analysis of variance with repeated measures on the last two factors.

PV angular errors were averaged across 3 consecutive reach training trials for each participant to form 10 bins of reach training trials in each Block. From these data, we first looked to establish that all participants reached in a similar manner during aligned reach training, (i.e. during Block 1, the baseline set of reach training trials), using a 2 Group (Strategy vs. No-Strategy) x 3 Rotation Size (20°, 40° vs. 60°) x 2 Bin (average of first 3 bins vs. average of last 3 bins) mixed analysis of variance with repeated measures on the last factor. Having established that all participants had similar PV angular errors during the baseline set of reach training trials, we then looked to analyze the sets of reach training trials completed when a cursor rotation was introduced (i.e. in Blocks 2 – 4), in order to determine if performance on reach training trials was dependent on Strategy or Rotation Size. Mean initial reach errors for each of these three sets of reach training trials were determined for each participant by averaging their PV angular error over the first three bins of trials (i.e. 9 trials in total) and then subtracting their average PV angular error achieved over the last three bins (i.e. 9 trials in total) in the aligned reach training trials performed in Block 1. Similarly, mean final reach errors in each set of rotated reach training trials were determined for each participant by averaging their

PV angular error over the last three bins of trials and then subtracting their average PV angular error achieved over the last three bins in the aligned reach training trials performed in Block 1. Mean errors were then subtracted from the magnitude of the distortion introduced (i.e. 20°, 40° or 60°), such that if a participant reached with a mean PV angular error of 60° and the cursor distortion introduced was 60°, then the participant would have a mean PV angular error of 0°. These reach errors with respect to the rotation size were submitted to a 2 Group (Strategy vs. No-Strategy) x 3 Rotation Size (20°, 40° vs. 60°) x 3 Block (the 1st vs. 2nd vs. 3rd set of 30 rotated reach training) x 2 Bin (average of first 3 bins vs. average of last 3 bins) mixed ANOVA, with repeated measures on the last two factors.

With respect to the PDP trials, RT and MT were analyzed using a 2 Group (Strategy vs. No-Strategy) x 3 Rotation Size (20°, 40° vs. 60°) x 2 Trial Type (exclusion vs inclusion) x 2 Bin (average of first 3 bins vs. average of last 3 bins) x 4 Block (Block 1, Block 2, Block 3 vs. Block 4) x 2 Time (initial vs. 5-minutes delay) mixed analysis of variance with repeated measures on the last three factors to determine if using a strategy was associated with slower RT and longer MT.

PV angular errors were collapsed across target positions and averaged across the 9 (i) inclusion or (ii) exclusion trials completed at the same time for each participant. Thus, in total, there were eight averages for each of the two types of trials for each participant. Average errors were used to first compute the index (i.e. the magnitude) of implicit and explicit contributions to visuomotor adaptation according to the following formulas:

$$\text{Implicit Index (II)} = M_{\text{Exclusion}}$$

$$\text{Explicit Index (EI)} = M_{\text{Inclusion}} - M_{\text{Exclusion}}$$

These indexes at each of the two time points (initial vs. 5-minute delay) following each of the sets of rotated reach training trials were then calculated relative to the corresponding index achieved following training with the aligned cursor in Block 1. Specifically:

$$\text{Implicit Adaptation Index} = (II_{\text{Rotation}} - II_{\text{Baseline}})$$

$$\text{Explicit Adaptation Index} = (EI_{\text{Rotation}} - EI_{\text{Baseline}})$$

Similar to Werner et al (2015), the adaptation indexes were also expressed relative to the extent a participant had adapted their reaches during the reach training trials. Specifically, the Implicit and Explicit Adaptation Indices for each participant in each rotated training block at the two time points were divided by the average PV angular error over the last three bins of reach training trials within the corresponding block of rotated reach training trials minus the average PV angular error for the last three bins of reach training trials within Block 1, the baseline block. To determine if the Implicit and Explicit Adaptation Indices changed with awareness, the magnitude of the distortion and/or over time, we performed a 2 Group (Strategy vs. No-Strategy) x 3 Rotation Size (20°, 40° vs. 60°) x 3 Block (following the 1st vs. 2nd vs. 3rd Block of 30 rotated reach training) x 2 Time (initial vs. 5-minute delay) mixed analysis of variance (ANOVA), with repeated measures on the last two factors for both the Implicit and Explicit Adaptation Indexes when expressed with respect to (i) magnitude, and (ii) relative to the extent of reach adaptation. Of note, data for one participant's explicit adaptation index at Time 1 and Time 2 following their first set (i.e. Block 2) of rotated reach training trials were more than 3 standard deviations away from the group's mean, and were therefore replaced by average performance across the remaining participants in the corresponding group (the 60°

Strategy group). For all analyses, differences with a probability of less than .05 were considered to be significant and Bonferonni post-hoc tests corrected for multiple comparisons were administered to find the locus of these differences for all pre-planned comparisons.

3. Results

3.1 Reach Performance during Reach Training Trials

With respect to the RT results during Reach Training, ANOVA revealed a main effect of Rotation Size ($F(2, 56) = 10.11, p < .001$), indicating that as the rotation size increased, RT became slower (20° Rotation: 314.83ms, 40° Rotation: 369.12ms, 60° Rotation: 446.54ms). ANOVA also indicated a main effect of Block ($F(3, 168) = 4.929, p = .003$), such that participants reacted the fastest during aligned reach training (Block 1; $M = 377.06$ ms), slowed down significantly during the first set of rotated reach training (Block 2; $M = 422.50$ ms), but reacted more quickly in the second set of rotated reach training (Block 3; $M = 369.31$ ms) and the third set of rotated reach training (Block 4; $M = 339.79$ ms). There was also a main effect of Bin ($F(1, 59) = 113.14, p < .001$), indicating that there was a slower RT during the initial Bin ($M = 451.22$ ms) as compared to the final Bin ($M = 303.11$ ms). ANOVA found no main effect of Group ($F(1, 56) = .02, p = .889$), such that the Strategy and No-Strategy groups had similar RT. However, a significant Group x Block x Bin interaction ($F(3, 168) = 6.24, p < .001$), revealed that there was a difference between the Strategy and No-Strategy group for Block 2 for the first bin (initial), such that participants in the Strategy group had slower RT when first exposed to the rotated reach training as compared to the No-Strategy group ($p = .020$). The two groups had similar RT for Blocks 1, 3 and 4 and the two Bins (initial vs. final; all $ps > .097$).

Similar to the RT results, for MT data, ANOVA revealed a main effect of Rotation ($F(2, 56) = 5.051, p = .01$), also suggesting that as the rotation size increased, MT was slower (20° Rotation: 821.77 ms, 40° Rotation: 893.85 ms, 60° Rotation: 997 ms). ANOVA also revealed a main effect of Block ($F(3, 168) = 43.951, p < .001$), such that participants had the fastest MT during Block 1 ($M = 785.85$ ms), slowed down significantly in Block 2 ($M = 1011.50$ ms) when they initially started with the rotated reach training, but had a faster MT during Block 3 ($M = 934.93$ ms) and Block 4 ($M = 884.45$ ms). There was also a main effect Bin ($F(1, 59) = 51.976, p < .001$), indicating a slower MT during the initial Bin ($M = 955.67$ ms) as compared to the final Bin ($M = 852.74$ ms). ANOVA found no main effect of Group ($F(1, 56) = .002, p = .962$), such that the Strategy and No-Strategy groups had similar MT.

In Figure 5 we see changes in mean PV angular errors over reach training trials when training with the 20° (A), 40° (B) or 60° (C) cursor rotation for participants in the Strategy group (dark gray line) and No-Strategy group (light gray line). For trials during Block 1 (baseline), when participants reached with a cursor that was aligned with their hand, we see that in general, all participants were fairly accurate in achieving the target, regardless of group or angle of rotation. Since the Strategy group only received their strategy following the baseline trials, we would expect there to be no differences between the Strategy and No-Strategy groups during Block 1. As expected ANOVA revealed that there was no significant main effects of Group ($F(1, 56) = 0.366, p = .547$), Rotation Size ($F(1, 56) = 2.302, p = .109$), or Bin ($F(1, 56) = 0.406, p = .527$) and no significant interactions (all p s $> .139$). Thus, all participants reached similarly during baseline, with a mean reach error of 2.55° ($SD = 1.87$) left of the target.

In contrast to fairly accurate performance when training with the aligned cursor, we see that when the cursor distortion was introduced, participants' reaches began to deviate to counteract the imposed cursor rotation. Moreover, from Figure 5, it appears that reaches began to deviate earlier on if participants were in the Strategy group. However, by the end of each block of rotated reach training trials, participants appeared to have similar errors regardless of whether they were provided with a strategy or not. In fact, by the end of the first block of rotated reach training trials with the 20° cursor rotation, participants in the Strategy group were reaching with an average PV angular error of 2.97° (SD = 0.80) compared to 3.99° (SD = 1.23) for the No-Strategy group. In accordance with these observations, ANOVA revealed a main effect of Group ($F(1, 56) = 10.86, p = .002$), such that participants in the Strategy group showed less error overall compared to the No-Strategy group. There was also a main effect of Block ($F(2, 56) = 24.69, p < .001$), and post-hoc analyses determined a difference between the first set of rotated reach training (Block 2) versus the second set of rotated reach training (Block 3; $p < .001$), and third set of rotated reach training (Block 4; $p < .001$), but not between the second and third sets of rotated reach training trials ($p = .897$). Thus, in general, participants decreased the amount of reach error over the course of Reach Training from Blocks 2 to 4. In addition, a main effect of Bin was found ($F(1, 56) = 33.872, p < .001$), suggesting that, in general, participants were more accurate in the final versus initial training trials across the sets of rotated reach training trials. There was no difference in reaching errors across the Rotation Sizes ($F(2, 56) = 0.465, p = .631$). However, ANOVA revealed significant Group x Rotation Size x Block ($F(4, 56) = 5.219, p = .002$), and Group x Rotation x Bin ($F(2, 56) = 5.197, p = .009$) interactions, with post-hoc analyses revealing that there were no differences for the 20°

Rotation between the Strategy and No-Strategy groups at any of the time points tested (all $p > .164$). In contrast, for the 40° and 60° Rotation Sizes, initial errors in the first set of rotated reach training trials (i.e. average of the first 3 bins) were larger in the No-Strategy group compared to the corresponding Strategy groups (both $p < .001$). For the 40° Strategy and No-Strategy groups, no further differences were found (all $ps > .200$), such that initial and final reach errors were similar in the second (Block 3) and third set (Block 4) of rotated reach training trials. As for the 60° Rotation Size, final errors differed between the Strategy and No-Strategy groups at the end of the first set of rotated reach training (Block 2, $p < .001$) and initial errors in the second (Block 3, $p < .001$) and third (Block 4, $p = .004$) set of rotated reach training differed as well, showing a continued advantage for the Strategy group. However, reach errors at the end of the second and third sets of rotated reach training (Block 3 and 4) did not differ between the groups (both $ps > .139$).

3.2 PDP Data

With respect to RT data, ANOVA showed significant main effects for Block ($F(3, 168) = 19.071, p < .001$), Rotation Size ($F(2, 56) = 6.061, p = .004$), and Trial Type ($F(1, 56) = 57.955, p < .001$). Participants were shown to react the fastest during aligned reach training ($M = 301.01$ ms), slowed down significantly following the first set of rotated reach training (Block 2; $M = 359.03$ ms), but reacted more quickly in the second (Block 3; $M = 335.25$ ms) and third (Block 4; $M = 328.17$ ms) sets of rotated reach training. Also, as the rotation size increased, participants tended to have a slower RT. For the Trial Type, participants consistently showed a faster RT when performing exclusion trials ($M = 304.23$ ms) compared to inclusion trials ($M = 357.5$ ms). As well, ANOVA detected a Block x Trial type ($F(2, 56) = 19.805, p < .001$), a Group x Rotation x

PDP ($F(6, 168) = 2.71, p = .015$), and a Rotation x Trial Type ($F(2, 56) = 11.099, p < .001$) interaction. Post-hoc analyses on the Block x Trial Type interaction, as expected determined no significant difference between the exclusion and inclusion trials during aligned reach training (Block 1; $p = .333$). However, the exclusion and inclusion trials consistently differed for the first (Block 2; $p < .001$), second (Block 3; $p < .001$) and third (Block 4; $p < .001$) set of rotated reach training. These results suggest that participants demonstrated faster RT during the exclusion trials, as compared to inclusion trials during rotated reach training trials. There were no significant main effects of Group or Time (both $ps > .082$).

For MT data, ANOVA also showed a main effect of Block ($F(3, 168) = 8.901, p < .001$), which demonstrated a similar pattern as the RT data, such that participants were shown to move fastest during Block 1 ($M = 933.22$ ms), slowed down significantly in Block 2 ($M = 1009.60$ ms), but had a faster movement time in Block 3 ($M = 969.619$ ms) and Block 4 ($M = 957.50$ ms). ANOVA also detected a main effect of Trial Type ($F(1, 56) = 46.269, p < .001$), such that participants had a slower MT during inclusion trials, and faster MT during exclusion trials. No main effects of Group ($F(1, 56) = 0.106, p = .746$) or Time ($F(2, 56) = 1.211, p = .276$).

3.2.1 ADAPTATION INDICES: MAGNITUDE

As seen in Figure 6, ANOVA revealed a main effect of Group ($F(1, 56) = 5.29, p = .025$), such that the No-Strategy group (Time 1: 20° Rotation Size $M = 9.3^\circ, SD = 1.35$, 40° Rotation Size $M = 8.9^\circ, SD = 1.54$ and 60° Rotation Size $M = 7.2^\circ, SD = 2.3$) had a greater implicit adaptation index compared to the Strategy group (Time 1: 20° Rotation Size $M = 7.8^\circ, SD = 1.63$, 40° Rotation Size $M = 5.0^\circ, SD = 1.11$ and 60° Rotation Size $M = 4.15^\circ, SD = 2.72$). Also as can be seen in Figure 6,

ANOVA revealed a main effect of Block ($F(2, 112) = 9.36, p < .001$), and post-hoc tests indicated that implicit processes after the second set of rotated reach training (Block 3) were greater than after the first set (Block 2, $p < .001$). There was no significant difference following the second and third set of rotated reach training trials (Blocks 3 and 4, $p = 1$), thus indicating that implicit processes took time to develop. Finally, as shown in Figure 6, there was a main effect of Time ($F(1, 56) = 37.66, p < .001$), suggesting that implicit processes decreased from when initially tested to when tested a second time following a 5-minute rest. Interestingly, we found no significant main effect of Rotation ($F(2, 56) = 2.56, p = .086$) and no significant interactions (all $ps > .168$), suggesting implicit processes were similar in magnitude for the three rotation sizes.

Explicit indices are shown in Figure 7. ANOVA revealed a main effect of Group ($F(1, 56) = 15.70, p < .001$), such that the Strategy group showed a greater explicit adaptation index than the No-Strategy group. ANOVA also revealed a main effect of Rotation Size ($F(2, 56) = 73.57, p < .001$), with post hoc analyses revealing that the explicit contribution was greater after training with a 60° Rotation compared to a 40° Rotation ($p < .001$), which was significantly greater than after training with a 20° Rotation ($p < .001$). There were no significant main effects of Block ($F(2, 112) = 0.398, p = .673$), or Time ($F(1, 56) = 0.496, p = .484$), and no significant interactions (all $ps > 0.133$). The lack of significant interactions suggests that as rotation size increased, explicit adaptation indices increased in a similar manner, regardless of whether participants were in the Strategy or No-Strategy group, with participants in the Strategy group displaying the greatest explicit adaptation index (Rotation Sizes of 20°: Strategy $M = 10.3, SD = 1.6$ and No-Strategy $M = .274, SD = 1.03$; Rotation Sizes of 40°: Strategy $M = 28.95, SD = 3.9$, and No-

Strategy M = 20.91, SD = 4.1; Rotation Sizes of 60° Strategy M = 51.23, SD = 7.67 and No-Strategy M = 37.69, SD = 2.72).

3.2.2 ADAPTATION INDICES: RELATIVE TO VISUOMOTOR ADAPTATION

Implicit Adaptation Indices observed in the final block (i.e. Block 4) expressed as a percentage of reach adaptation achieved are shown in Figure 8. These results appear to differ from those presented in Figure 6. Specifically, while the No-Strategy group had a greater implicit contribution to visuomotor adaptation, both groups showed decreases in implicit contributions with increasing Rotation Size (e.g. No-Strategy group for the 20° Rotation Size M = 0.676, SD = 0.57, 40° Rotation Size M = 0.267, SD = 0.21, and 60° Rotation Size M = 0.122, SD = 0.07, compared to the Strategy group for the 20° Rotation Size M = 0.462, SD = 0.37, 40° Rotation Size M = 0.162, SD = 0.31, and 60° Rotation Size M = 0.061, SD = 0.07). ANOVA revealed main effects of Group ($F(1, 56) = 4.58, p = .037$), Rotation Size ($F(2, 56) = 23.28, p < .001$), Block ($F(2, 112) = 3.181, p = .45$) and Time ($F(1, 56) = 35.93, p < .001$). The factor of Rotation was not surprising given the findings above, as participants altered their reaches more to counteract the larger distortions. Post hoc analyses showed that when the implicit indices were expressed relative to reach adaptation, indices were greater for the 20° vs. the 40° ($p < .001$) and 60° Rotations ($p < .001$), however the indices for the 40° and 60° were not significantly different ($p = .292$). Implicit processes also took time to develop, such that indices were greater in Block 4 vs. Block 2 ($p = .24$), however the indices for Block 2 and 3 ($p = .361$), as well as Block 3 and 4 ($p = .956$) were not significantly different. Similar to the results reported previously, participants in the No-Strategy group showed a greater contribution from implicit processes than the Strategy group, and that the implicit contribution decayed from initial PDP

trials to the PDP trials following the 5-minute rest. No other significant interactions were detected, the closest was a Time x Strategy interaction (all p s > .053).

Explicit Adaptation Indices achieved in Block 4 relative to reach adaptation are also shown in Figure 8. Similar to results discussed above with respect to explicit adaptation indices, ANOVA revealed main effects of Group ($F(1, 56) = 28.42, p < .001$), and Rotation Size ($F(2, 56) = 11.13, p < .001$). Specifically, the Strategy group showed a greater contribution of explicit processes, and that explicit contributions increased as rotation size increased. In addition, there was a Group x Rotation interaction ($F(2, 56) = 3.701, p < .031$). Post hoc analysis of the Group x Rotation interaction revealed that the No-Strategy group's explicit contributions increased from the 20° ($M = .020, SD = 0.66$) to 40° ($M = .621, SD = 0.24$) ($p < .001$) Rotation Sizes and from the 20° to 60° Rotation Sizes ($M = .950, SD = 0.42$) ($p < .001$), but not from the 40° and 60° Rotation Sizes ($p = 1$). The Strategy Group showed similar explicit contributions regardless of training with the 20° ($M = .742, SD = 0.67$), 40° ($M = .865, SD = 0.34$), and 60° ($M = 0.950, SD = 0.14$) Rotation Sizes (all p s > .422). No other main effects or interactions were significant (all p s > .212).

3.2 Post-Experiment Questionnaire Data

Results from the post-experiment questionnaire classified most participants as being aware if they reported i) being aware of the distortion, or ii) claimed to have used a strategy (i.e. "pushed" his or her hand left in order to successfully land the cursor on the target). All participants in the Strategy group were classified as being aware of the presence of a distortion, which was expected since they had been provided with a strategy to counter their respective

rotation. However, there were some notable differences for the No-Strategy group, such that only 2 of 11 participants were classified as aware when training with a 20° Rotation. As for the 40° and 60° Rotation Sizes, 9 out of 10, and 8 out of 10 were aware, respectively. Therefore, it seems participants became aware of the distortion indirectly with the larger rotation sizes.

4. Discussion

The main objectives of the current experiment were to assess the contributions of explicit and implicit processes to visuomotor adaptation when awareness was manipulated directly and indirectly, and determine if these contributions changed over time. Participants were assigned to a Strategy or No-Strategy group, and assigned to train with one of three Rotation sizes (20°, 40°, or 60°). Following sets of reach training trials, participants completed reaches without visual feedback within a Process Dissociation Procedure (PDP) framework. Using this framework, we were able to establish changes in contributions of explicit and implicit processes to visuomotor adaptation across participants. Our results initially revealed that regardless of the distortion size, participants successfully adapted to their respective rotation size during reach training trials, and that these changes were mostly accounted (~93%) for by the sum of explicit and implicit indices to reach adaptation as seen in the PDP trials. As determined by the PDP trials, participants assigned to the No-Strategy group demonstrated greater implicit learning than participants within the Strategy group. Interestingly, the magnitude of participants' implicit adaptation indices did not vary across rotation sizes. This indicates a similar degree overall of implicit learning regardless of the size of reach error initially experienced, but also smaller implicit contributions with increasing rotation size. This implicit learning took time to develop, and decayed quickly. In contrast, explicit contributions to

visuomotor adaptation were greater in the Strategy group compared to the No-Strategy group and increased in magnitude with rotation size. In fact, the increase scaled with the extent of reach adaptation for the Strategy group, such that the explicit contribution expressed relative to the extent of reach adaptation did not vary across rotation sizes. In contrast, the explicit contribution expressed relative to the extent of reach adaptation varied with rotation size for the No-Strategy Group, such that the greatest contribution was seen in the group that trained with the 60° distortion. Therefore, our results suggest that awareness, provided directly by way of a strategy or indirectly by changing rotation size can modify the contributions of explicit and implicit processes to visuomotor adaptation.

Explicit and Implicit Contributions to Visuomotor Adaptation

Traditionally, explicit (and hence implicit) contributions to visuomotor adaptation have been assessed by comparing performance between participants who are classified as aware versus unaware of the presence of the distortion based on post-experiment questionnaires (Benson et al, 2011). For example, participants are asked if they noticed a change in the task following completion of the experiment. If participants indicate that the task became more difficult, they are then further probed on the perturbation itself. If they are able to indicate and describe (or draw) how the cursor movement did not correspond with the intended cursor trajectory, they are classified as being “aware” of the perturbation (Benson et al, 2011; Heuer & Hegele, 2008; Hwang, Smith, & Shadmehr, 2006; Werner et al, 2015). Results from participants classified as aware are then contrasted with participants classified as unaware and the role of explicit/implicit contributions to visuomotor adaptation determined. Using a similar questionnaire, we classified participants assigned to the Strategy group as aware, as well as the

majority of participants in the No-Strategy group who trained with the 40° and 60° Rotation Sizes. Participants who trained with the 20° Rotation Size and were not instructed on the perturbation remained unaware of the distortion based on our post-experiment questionnaire.

This classification of participants as aware vs. unaware differed from the results attained in the PDP trials, recently introduced by Werner and colleagues (2015) to quantify explicit and implicit contributions to visuomotor adaptation. Similar to Werner and colleagues, our participants were provided with instructions during the no-cursor PDP reaching trials such that they were to: use what they had learned during reach training (Inclusion trials) or reach like they had during the baseline block (Exclusion trials). By contrasting results between these sets of trials, we were able to establish explicit and implicit contributions to visuomotor adaptation at different points during reach training (e.g. after every 30 trials and following a 5-minute delay). Within these trials, we found that all participants provided evidence (albeit limited for some groups of participants) of explicit and implicit contributions to visuomotor adaptation, implying that the classification of aware versus unaware based on post-experiment questionnaires may be too strict.

Overall, we found that explicit contributions played a larger role in visuomotor adaptation compared to implicit contributions across all participants (Mean Explicit = 0.64 versus Mean Implicit = 0.29). With respect to the role of explicit processes in visuomotor adaptation, we found greater explicit adaptation indices in our Strategy compared to No-Strategy group. When these indices were expressed relative to the extent of reach adaptation, we found that explicit contributions did not vary across rotation size for the Strategy group, but

did increase across rotation size for the No-Strategy group. Thus, explicit contributions varied when awareness was provided directly by way of a strategy and indirectly by varying rotation size. However, there was no additional benefit of indirect awareness for the Strategy group. In contrast to Werner et al (2015), we found a greater contribution of implicit processes for our No-Strategy group compared to our Strategy group, regardless if implicit indices were expressed with respect to overall magnitude or relative to participants' extent of reach adaptation. Moreover, in line with results reported by Bond and Taylor (2015), we found that the magnitude of implicit processes appeared to achieve a ceiling, such that there was a maximum amount they could contribute to visuomotor adaptation.

In the experiment by Bond and Taylor (2015), implicit processes were assessed through no-cursor reaching trials (in which participants were instructed to aim to the target), following reach training trials with a cursor rotation of 15° to 90°. Within the reach training trials, participants had to verbally report the location they planned to aim to in order for the cursor to hit the target by using landmarks provided on each trial prior to reaching. Bond and Taylor (2015) then contrasted the reported location with the location participants aimed to, in order to determine the extent of explicit and implicit contributions during visuomotor adaptation. Finally, the implicit contribution could be compared with implicit processes assessed through aftereffect trials. During the reach training trials participants showed both explicit and implicit contributions to visuomotor adaptation, and the extent of implicit contributions at the end of reach training was similar to what was seen in their aftereffects trials (between 8°-12°, regardless if participants trained with a cursor that was rotated 15° or 90°). The implicit adaptation index in our No-Strategy group was similar in magnitude at 6°-10°. In contrast, the

implicit adaptation index was lower in our Strategy group (approximately 5° overall). This difference between groups is not surprising, given that implicit processes have been suggested to play a smaller role in visuomotor when strategies are provided directly (Benson et al, 2011). Thus, it appears that when explicit processes are engaged from the beginning, implicit processes do not have the same opportunity to develop and contribute to visuomotor adaptation as when awareness is developed indirectly.

Potential differences in our paradigm from Werner et al (2015) that may account for why we found that direct and indirect manipulations of awareness led to differences in the contribution of implicit processes to visuomotor adaptation have to do with participants' level of awareness and experimental design. Most of our participants in the 40° (9 out of 10 participants) and 60° (8 out of 10 participants) rotation sizes in the No-Strategy group were classified as being aware of the distortion (or having used a strategy, usually indicating they “pushed left” to land the cursor on the target). In their experiment, Werner et al (2015), reported that only 7 out of 16 (or 44%) participants became aware of the perturbation. Moreover, it is unclear which perturbation their participants became aware of, as they were only probed for awareness using the post-experiment questionnaire following training with all three perturbations. The fact that participants trained on all three perturbations in the experiment by Werner et al (2015), also differs from our current experiment. This training, and the potential recognition of a perturbation, may have shifted how some of their participants behaved across the experiment. Specifically, although the order of the presentation of the three rotation sizes was counterbalanced across participants, it is possible for interference to have occurred across rotations sizes, as participants were required to learn three different

visuomotor rotation tasks in the same session. Specifically anterograde interference, which refers to impairment in learning a second task following learning of a first task, has been shown when participants were required to learn two force field perturbations one after the other (Sing & Smith, 2010).

Our data also differs from the results presented by Werner et al (2015) in that we show that the measures reported in our implicit and explicit adaptation indices approximately sum to the extent of reach adaptation observed (i.e. the sum of Implicit and Explicit Adaptation Indices was approximately 1.08 for the Strategy group and 0.75 and for the No-Strategy group), whereas the values reported by Werner and colleagues appear to be approximately 0.80 for their Strategy group and 0.55 for their No-Strategy group. Thus, it appears that the implicit and explicit indices reported by Werner and colleagues (2015) do not entirely account for the changes in reaches observed during the reach training trials. Unfortunately, data related to the extent of implicit and explicit contributions and reach adaptation are not provided in the experiment by Werner and colleagues (2015), but rather expressed in relation to each other. Thus, it is difficult to determine if differences in results may also lie in the extent of reach adaptation achieved across the two experiments. Based on our results, it seems that reach adaptation can almost be entirely accounted for by the Explicit and Implicit Adaptation indices, especially when participants are provided with a strategy.

Time Course of Explicit and Implicit Contributions to Visuomotor Adaptation

Within the current experiment we looked to evaluate explicit and implicit contributions to visuomotor adaptation across time. In their paradigm looking at explicit and implicit

contributions across reach training trials, Taylor et al (2014) showed that implicit processes took time to develop during reach training such that implicit processes slowly increased between trials 56 to 376. Moreover, as pointed out earlier, they suggested that implicit contributions to reach adaptation achieved a ceiling effect during reach training, which did not scale with the magnitude of the distortion. Similar to these results, we found that implicit processes took time to develop while training with a distortion, such that implicit processes were greater after 60 versus 30 reach training trials with a rotated cursor. Moreover, we found that these implicit processes decayed quickly such that a significant decrease in implicit indices was found when tested for a second time following a 5-minute break where participants sat quietly between the two sets of PDP trials. These results are also in line with Taylor and Bond (2015), as from examining their data, it appears that errors in their aftereffect trials decayed over the course of 40 trials, although this is only an observation since Bond and Taylor (2015) did not analyze performance in their aftereffect trials over time.

With respect to the timing of explicit contributions to visuomotor adaptation, we found that our participants who were provided with a strategy demonstrated an immediate performance advantage in the reach training trials compared to those participants who were not provided with a strategy. However, this initial performance advantage disappeared within 30 reach training trials, such that by the end of the first set of reach training trials with the 20° or 40° rotated cursor, participants aimed in a similar manner regardless of whether they had been provided with a strategy. For participants who trained with the 60° rotation size, it took approximately 2 sets of reach training trials for participants in the Strategy and the No-Strategy group to achieve similar performance. Regardless of differences in reach training trials across

blocks, we found that the contribution of explicit processes to visuomotor adaptation as assessed through PDP trials did not differ across the 3 blocks of rotated reach training and did not decay when a 5-minute delay was inserted following reach training.

Modeling Explicit and Implicit Contributions to Visuomotor Adaptation

Current models would suggest that, in general, there are two processes working in parallel, but on different timescales that contribute to motor adaptation (Hwang et al., 2006; McDougle et al., 2015; Redding & Wallace, 1996, 2001, 2002). Specifically, Redding and Wallace (2001) proposed two distinctive adaptive processes based on prism adaptation results: a strategic perceptual-motor control process and an adaptive spatial alignment process. Specifically, the first process is proposed to arise consciously (or with awareness) and contributes quickly to motor adaptation by reducing initial reach errors. In contrast, the second process, persists throughout adaptation by slowly and gradually reducing movement error (McDougle et al, 2015; Trewartha et al, 2014). Furthermore, implicit processes engaged during reach training would be responsible for errors seen in aftereffect trials, when participants were instructed to aim to the target. In line with models detailing explicit and implicit contributions to visuomotor adaptation, Smith and colleagues' (2006) two-state model indicates that there are two processes that contribute to motor adaptation, which operate on different time scales. Specifically, they put forth that a fast process (that quickly reduces initial direction error and decays quickly) and a slow process (that reduces movement error slowly and gradually) underlie motor adaptation. Recently, McDougle et al. (2015) have linked these fast and slow processes to explicit and implicit processes in visuomotor adaptation respectively. In line with these models, our results suggest that explicit and implicit processes worked in parallel to

contribute to visuomotor adaptation. Additionally, our results revealed that implicit processes took time to develop. However, these models do not seem to reflect, nor predict the decay we saw in the implicit trials over time, nor the consistent contribution of explicit processes to visuomotor adaptation we observed in our PDP trials. One possible explanation is that the fast process put forth by Smith et al. (2006) has both explicit and implicit components, and does not necessarily reflect an explicit process alone (as was indicated by McDougale and colleagues). Thus, as suggested by Zbib et al (2016), the decay that we see in our implicit indices over a 5-minute rest interval reflects a decay of the (implicit) fast process.

Assessing Explicit and Implicit Contributions to Visuomotor Adaptation

Based on our results, it appears that there is the potential for explicit and implicit processes to contribute to errors observed in no-cursor reaches (i.e. traditional aftereffect trials), depending on the instructions provided. In particular, it seems that when participants are not made aware of the distortion and the rotation size is small, primarily implicit processes are engaged during visuomotor adaptation and are reflected in aftereffect trials (regardless of instruction). However, with a large distortion (i.e. 40° or greater) that is introduced abruptly, there is the potential for participants to become aware of the distortion, and hence this awareness to influence their no-cursor reaches. In fact, Bond and Taylor have attributed the fact that they did not find changes in implicit processes that scaled with rotation size (as shown previously by Thomas & Bock, 2012), based on the fact that they instructed participants that the distortion had been removed and they were to aim to the target, as opposed to merely removing the distortion. Using similar instructions to Bond and Taylor (i.e. in our Exclusion trials), we also found that implicit processes achieved a ceiling and did not scale with rotation

size. Thus, future research needs to carefully consider the impact that instructions can have on results and consider if aftereffect trials reflect implicit, explicit and/or a combination of implicit plus explicit processes.

It is important to note that within our current experiment and the experiments by Taylor and colleagues (Taylor et al. (2014); Bond & Taylor (2015)), in which participants reported aiming direction on each reach training trial, participants were asked to think about the task continually. Specifically, in our experiment, participants were instructed to a) reach to the target with a strategy or any information they may have picked up, and b) to reach as they would have during baseline, after every 30 reach training trials. While we wanted to test for explicit and implicit contributions on an ongoing basis to establish a timeline, these trials may have indicated to our No-Strategy participants that the environment they were reaching in had (or was going) to change, which may in turn have influenced their awareness of the distortion. Notably this assessment was also done in the baseline block, prior to reach training with a rotated cursor, which again could have cued participants that something was going to change. Future research should consider if providing such instructions influences performance.

Conclusion

By manipulating awareness directly and indirectly, we found that explicit and implicit contributions to visuomotor adaptation were modified. Specifically, providing awareness directly via a strategy resulted in greater explicit contributions to visuomotor adaptation and smaller implicit contributions. Along the same lines, manipulating awareness indirectly by increasing the rotation size, resulted in increased explicit and decreased implicit contributions

to visuomotor adaptation for the No-Strategy group. However, explicit contributions remained at a similar level regardless of rotation size for the Strategy group, while implicit contributions decreased with increasing rotation size. Importantly, implicit contributions took time to develop and did not increase in magnitude across rotation sizes, implying a ceiling level, whereas explicit contributions did not change with time and increased in magnitude with rotation sizes. These differences in the No-Strategy vs. Strategy groups were observed even though the majority of participants were classified as aware of the perturbation on a post-experiment questionnaire. Taken together our results suggest that awareness, regardless of whether it is acquired through direct or indirect manipulations, is detrimental to implicit contributions to visuomotor adaptation, as explicit processes tend to dominate.

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Figures

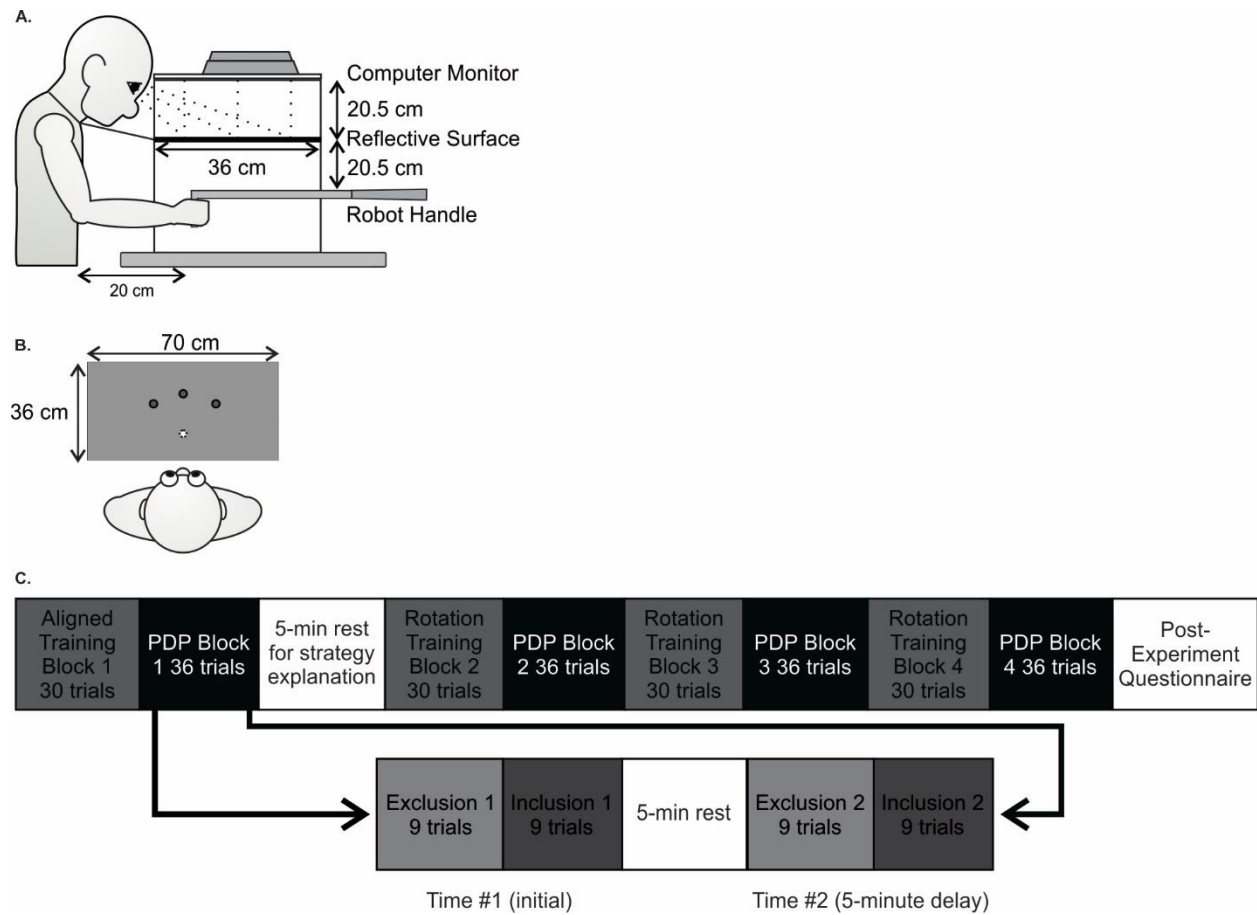


Figure 1. Experimental Set-Up and Design

(A): Side-view of the experimental set-up. Participants were instructed to grasp the handle of the robot manipulandum with their right hand. (B): Top-view of the apparatus illustrating the dimensions of the experimental workspace. The home position (as represented by the dotted white circle) was not visible to participants throughout testing. The three reach targets (2 cm in diameter white circle), were located straight ahead, 40° clockwise (CW) and 40° counter-clockwise (CCW) relative to straight ahead, at a distance of 15 cm from the home position. During reach training trials with the rotation, the cursor representing the participants’ reach trajectory (as represented by a green circle, 1 cm in diameter) was rotated 20°, 40° or 60° CW relative to the home position. (C) Overall breakdown of testing blocks completed by all participants, and breakdown of one set of PDP trials. The order of “exclusion” and “inclusion” trials was counterbalanced across participants. In addition, the order of these trials was the same for Time 1 (initial) and Time 2 (5-minute delay), such that half of the participants started with exclusion trials, the other half started with inclusion trials.

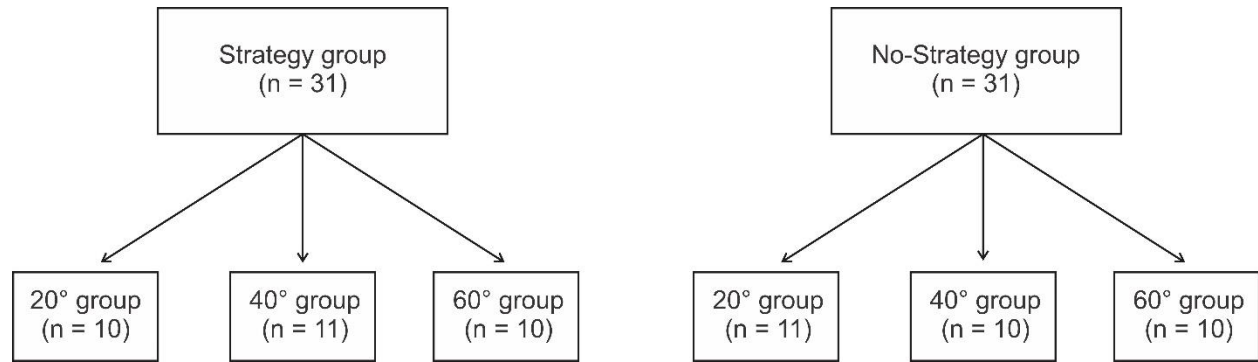


Figure 2. Breakdown of participants

Participants were randomly assigned to one of two groups, either a Strategy group or No-Strategy group. These participants were then further subdivided into 3 additional groups to train with one of three rotation sizes (6 groups in total): 20°, 40°, or 60° CW. n corresponds to the number of participants in each group.

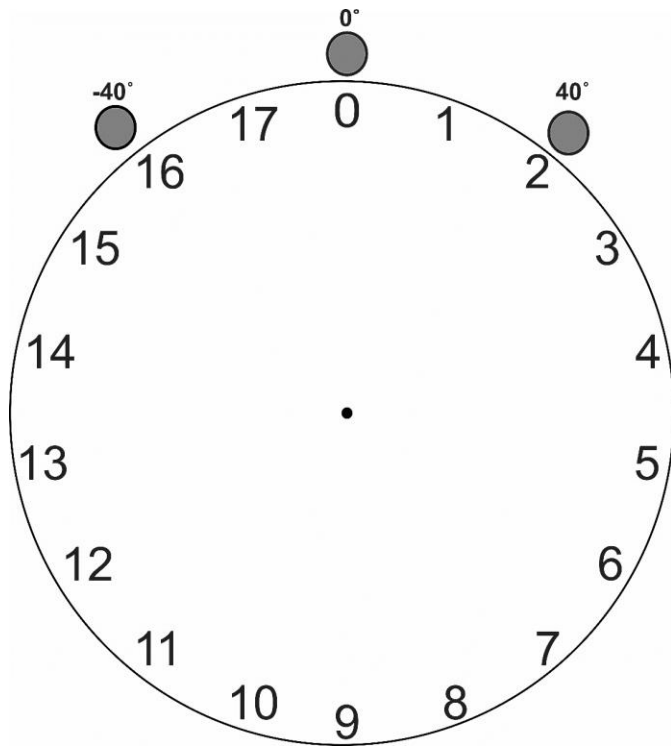


Figure 3. Clock face provided for Strategy Group

Modified clock face that was used to instruct the Strategy group as to the nature of their respective rotation (20°, 40° or 60° CW). Participants in the Strategy group were explicitly instructed during the rotated reach training trials that their cursor was rotated in the clockwise direction, and told how to counteract the rotation of the cursor so that they could land the cursor on the target. For example, participants in the 40° subgroup were explicitly instructed to aim their hand towards the 0 to counteract their rotated cursor if they were trying to aim to the right (or 40° CW) target location. Then, participants would draw on the clock face how to counteract the perturbation for the two other target locations to show that they understand the instructions prior to completing the rotated reach training trials. The gray circles represent the three target locations. The 16 on the clock face corresponds to the 40° CCW target, 0 corresponds to the center target, and the 2 corresponds to the 40° CW target.

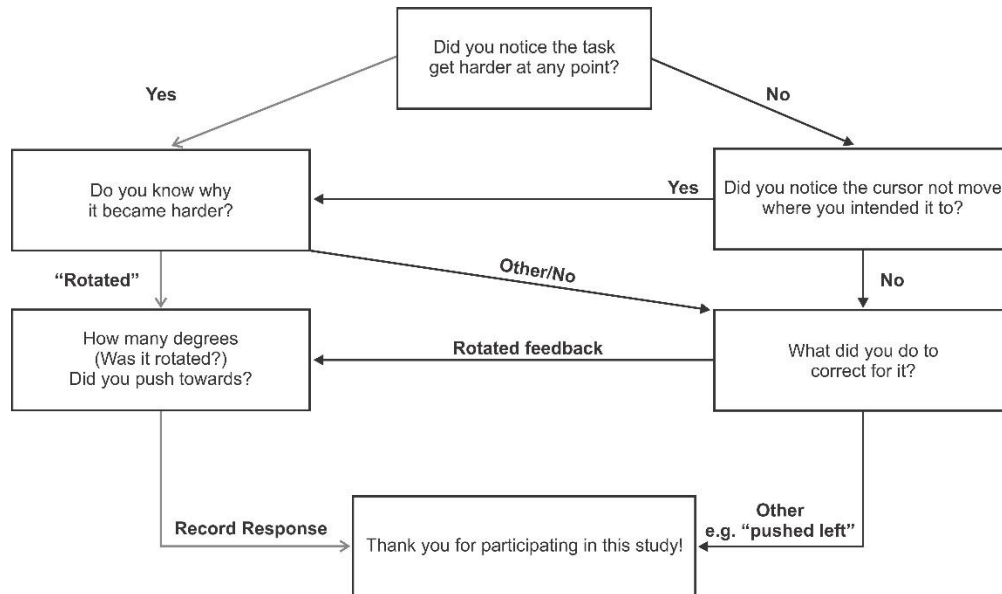


Figure 4. Post-Experiment Questionnaire

The post-experiment questionnaire that was provided to all participants at the end of the experiment to assess awareness, as used by Benson et al (2011). The participants were classified as being explicitly aware if they were considered to have used a strategy (i.e. followed the left path on the diagram and claimed to have used a strategy to counteract the perturbation, reported the difference in the intended reach trajectory or characterized a perturbation as being a rotation). All other participants were classified as not aware (i.e. followed the right path on the diagram and were unable to identify any information or strategy used).

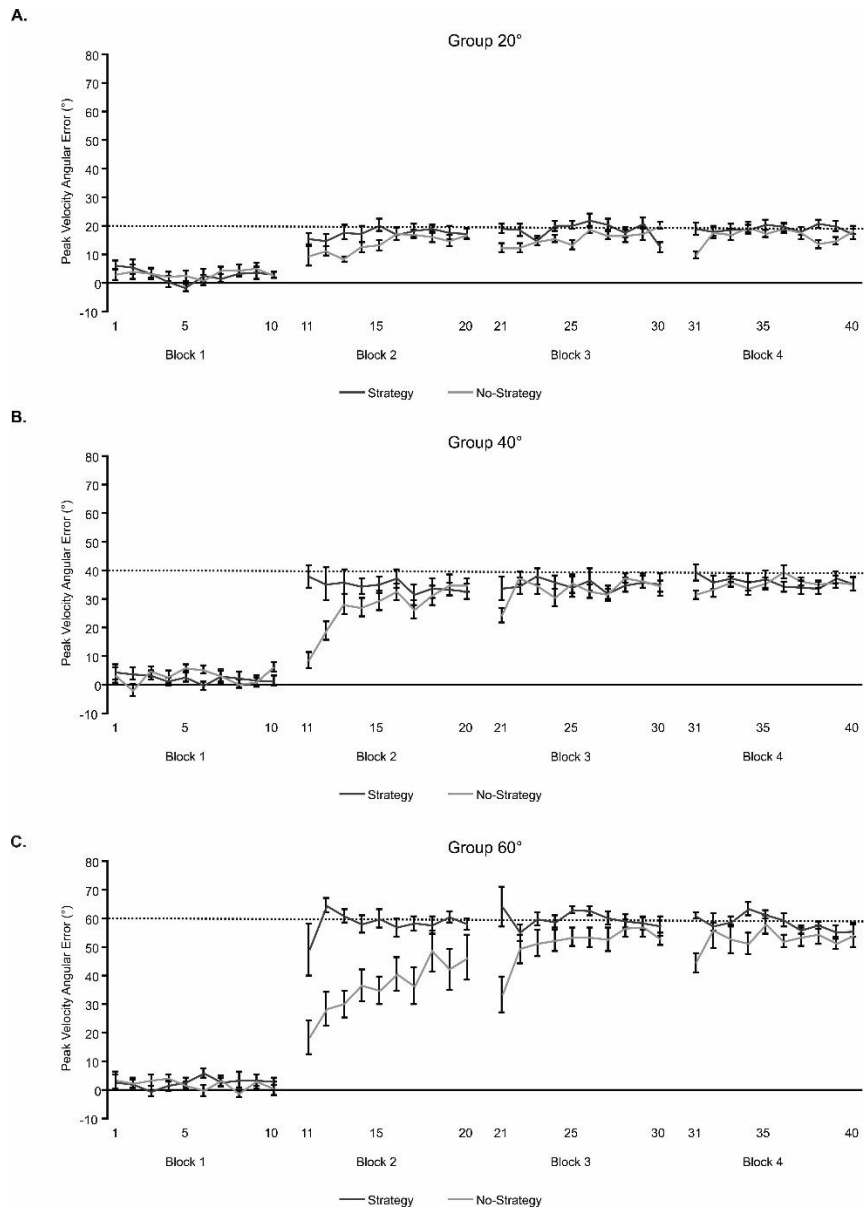
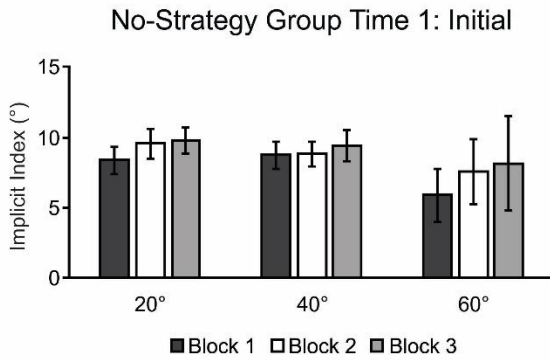


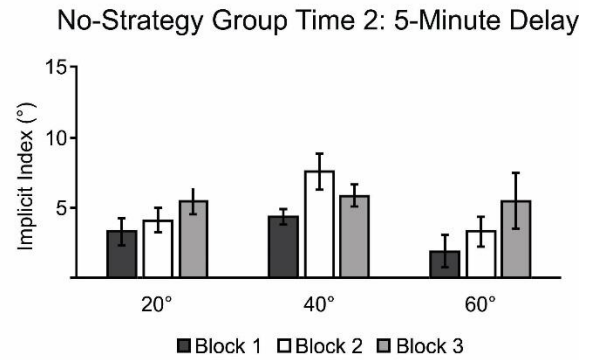
Figure 5. Reach Training Results

Mean PV angular errors when participants trained with a cursor that was aligned (Block 1) or rotated clockwise relative to the hand (Blocks 2, 3, 4) by 20° (A), 40° (B), or 60° (C). If participants adjusted their movements to counteract the distortion, reach errors would be around the dotted line in each figure. The results are presented such that each point represents the average across three trials (i.e. 1 bin). The black lines correspond to results of the Strategy groups and grey lines correspond to the results of our No-Strategy groups. Error bars represent standard error of the mean. If participants corrected their reaches in order to account for the perturbation, reach errors would fall along the dashed lines.

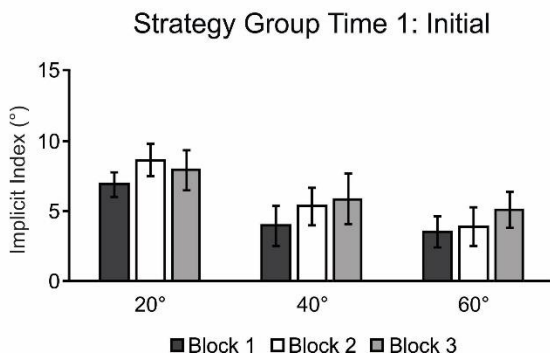
A.



B.



C.



D.

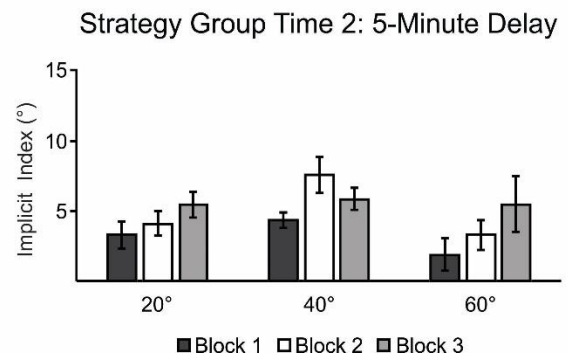
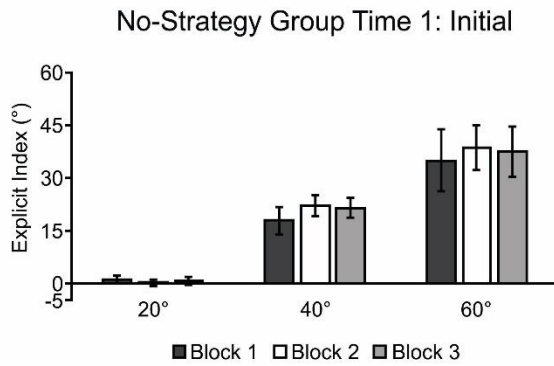


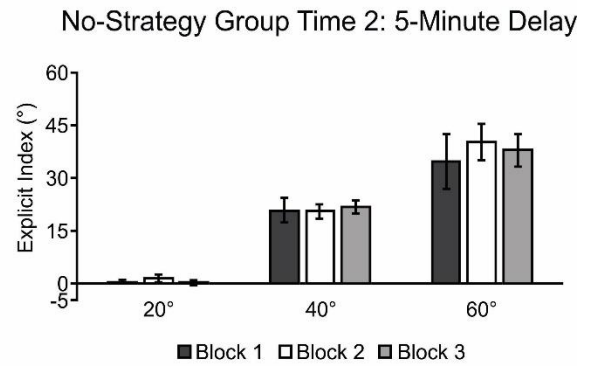
Figure 6. Implicit Adaptation Index

Mean Implicit adaptation indices broken down by Group (No-Strategy groups shown in **(A)** and **(B)** and Strategy groups shown in **(C)** and **(D)**) and Time (Time 1 in left column and Time 2 in right column). For each plot, the dark grey, white and light grey bars represent the results of the first, second and third rotated reach training blocks (i.e. Blocks 2, 3 and 4), respectively. Results are separated for each Rotation Size. Error bars indicate standard error of the mean.

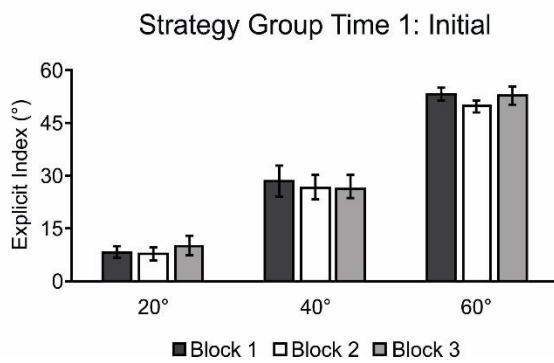
A.



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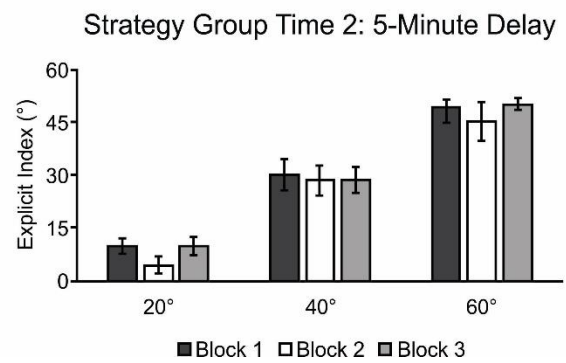


Figure 7. Explicit Adaptation Index

Mean Explicit adaptation indices broken down by Group (No-Strategy groups shown in **(A)** and **(B)** and Strategy groups shown in **(C)** and **(D)**) and Time (Time 1 in left column and Time 2 in right column). For each plot, the dark grey, white and light grey bars represent the results of the first, second and third rotated reach training blocks (i.e. Blocks 2, 3 and 4), respectively. Results are separated for each Rotation Size. Error bars indicate standard error of the mean.

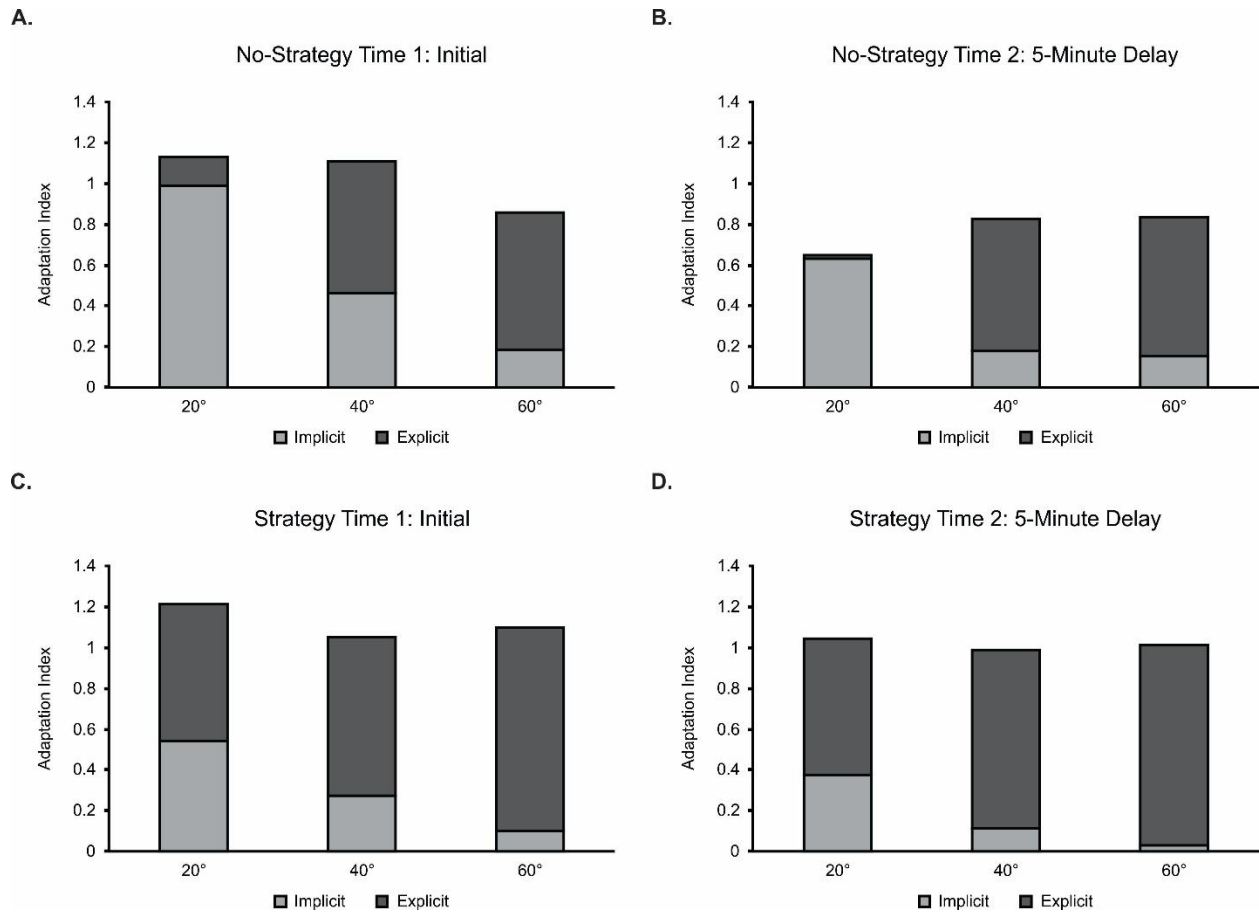


Figure 8. Adaptation indices expressed as a percentage relative to the participants' reach

Mean Implicit and Explicit adaptation indices relative to the extent of visuomotor adaptation in the last Block of trials. Results are broken down by Group (No-Strategy groups are shown in **(A)** and **(B)** and Strategy groups are shown in **(C)** and **(D)**) and Time (Time 1 in left column and Time 2 in right column). The light grey represents the percentage of implicit contributions and the dark grey represents explicit contributions to visuomotor adaptation when expressed as a percentage of reach adaptation.

Chapter III: General Discussion

When participants reach with distorted visual feedback of their hand in the form of a visual cursor on a screen, they adapt their reaches, so that they accurately land the cursor on the target. The current experiment sought to first establish how awareness (directly or indirectly provided) influences the contributions of explicit and implicit processes to visuomotor adaptation, as measured through a series of aftereffects trials. The experiment also looked to determine the time course for implicit and explicit contributions to visuomotor adaptation. In general, our results showed that explicit contributions played a larger role in visuomotor adaptation than implicit contributions, when participants were made aware of the distortion directly or become aware indirectly because a larger distortion was introduced. In contrast, implicit contributions played a larger role when the distortion was small and participants were unaware of the perturbation. However, regardless of awareness, both explicit and implicit processes were shown to contribute to visuomotor adaptation.

We found notable differences between explicit and implicit contributions to visuomotor between participants who were provided with a strategy, compared to those who were not instructed on the perturbation. Specifically, participants displayed more explicit and less implicit contributions to visuomotor when provided with a strategy compared to the No-Strategy participants (even if they became aware of the perturbed visual feedback indirectly). These same results held regardless if contributions were expressed as a percentage of reach adaptation achieved or overall magnitude. Similarly, varying awareness indirectly by manipulating distortion size led to greater explicit and lower implicit contributions to visuomotor adaptation for the No-Strategy group. In contrast, manipulating rotation sizes did

not change the contribution of explicit processes to visuomotor adaptation for the Strategy group. Taken together, these results demonstrate that awareness provided directly or indirectly can modulate explicit and implicit processes to visuomotor adaptation.

As implied above, the results of the PDP trials were analyzed with respect to their contribution to visuomotor adaptation and with respect to their overall magnitude. Interestingly, we found that if we expressed our results with respect to magnitude, that while the amount of implicit learning differed between the Strategy and No-Strategy groups, it did not vary across rotation sizes. This result replicates previous findings by Bond and Taylor (2015), who found that implicit processes reached a ceiling of approximately 12° , regardless if participants trained with a 15° , 30° , 60° or 90° rotation size. While, the current experiment reported a ceiling of approximately 10° in the No-Strategy group across all rotations, it remains unclear how implicit processes would be modulated if participants remained unaware when reaching with larger distortion sizes.

Most participants in our 40° , and 60° No-Strategy group were classified as being aware via the post-experiment questionnaire. This awareness was likely achieved because we introduced the cursor rotations abruptly (such that on the first reach training trial the full 40° or 60° rotation was introduced). If a rotation is introduced gradually, participants are less likely to become aware of the perturbation, as seen by Kagerer et al (1997). Thus, having participants train with a gradually introduced visuomotor distortion and then assessing explicit and implicit contributions to visuomotor adaptation through PDP trials, would be one way to determine if implicit processes can be modulated across rotation sizes in the absence of awareness. It is

possible that implicit processes would differ if participants were less aware (or unaware) of the perturbation, such that they would increase with the distortion size.

Predictions of Explicit and Implicit Contributions in Motor Adaptation Based on Motor Adaptation Models

Models of motor adaptation would suggest a role for both explicit and implicit contributions. In general, most models indicate that these two processes work in parallel, but at different time scales (McDougle et al., 2015; Redding & Wallace, 1996, 2001, 2002; Taylor et al., 2014). PDP trials seem to be able to tap into and measure these processes working in parallel, and based on our design, the timeline for engaging these processes can be determined. Specifically, with respect to timing, we found that implicit processes took longer to be engaged. In contrast, explicit contributions were present from the beginning and did not change over the course of reach training, demonstrating the robustness of explicit contributions to visuomotor adaptation.

While current models of motor adaptation can account for our results in general, they do not predict or explain the decay we saw in our implicit processes within 5 minutes. This decay can potentially be explained by the processes proposed by Smith et al (2006) in their two-state model. According to the two-state model there is a fast process, which leads to a quick reduction in initial reaching error, as well as a slow process that gradually and slowly reduces movement error. The decay that we see in our implicit indices over a 5-minute rest interval may reflect a decay of the (implicit) fast process put forward by Smith et al. (2006), suggesting that

perhaps there is three processes that underlie motor adaptation (e.g. an explicit process and two implicit processes (a fast and a slow process)).

The Role of Questionnaires and Instructions on Explicit and Implicit Contributions to Visuomotor Adaptation

Traditionally, studies have classified participants as aware or unaware based on a post-experiment questionnaire and then compared performance across participants assigned to the aware (or “explicit”) versus unaware (or “implicit”) groups (Benson et al., 2011; Hwang et al., 2006). From our results, we see that all participants showed evidence of explicit and implicit contributions to visuomotor adaptation, which implies that classifying participants into an aware versus unaware group based on a post-experiment questionnaire may be too strict. Given that, it is unclear how participants would have been previously classified if they became indirectly aware of the distortion and how their results could have potentially influenced previous reports regarding implicit and explicit contributions to visuomotor adaptation.

Future studies should consider the impact that instructions can have on results and their interpretation. Specifically, depending on instructions in aftereffect trials, results may reflect implicit, explicit and/or a combination of implicit plus explicit contributions. While we wanted to establish a timeline for explicit and implicit contributions to visuomotor adaptation, inserting PDP trials throughout reach training trials may have indicated to our No-Strategy participants that the environment they were reaching in had (or was going) to change, which may in turn have influenced their awareness of the distortion. Moreover, this assessment was also done in the baseline block, prior to reach training with a rotated cursor, which again could have cued

participants that something was going to change. It needs to be determined if providing such instructions influences one's performance.

Summary

To conclude, based on the current experiment, participants can acquire awareness through either direct (i.e. provided with a strategy) or indirect (i.e. varying the magnitude of the distortion) manipulations and how this awareness is achieved can modulate explicit and implicit processes. More specifically, making participants aware of a distortion directly via a strategy leads to greater explicit contributions compared to participants who are not provided with a strategy, regardless if they are classified as aware using a post-experiment questionnaire. Furthermore, direct awareness is detrimental to implicit contributions to visuomotor adaptation. Similarly, indirect awareness is also detrimental to implicit contributions to visuomotor adaptation, but not to the same degree as direct awareness.

From a practical standpoint, understanding the role of strategic processes, awareness and instructions on motor performance is important. For example, consider an applied setting, such as a rehabilitation clinic, where a patient is trying to relearn how to use their hand following a stroke. If the goal is for the patient to relearn the task as quickly as possible, then they should be provided with explicit instructions (i.e. a strategy). However, if the goal is for the patient to achieve a more autonomous level of learning, as proposed by Fitts and Posner (1967), then instructions should not be provided. Notably older adults would benefit from such a method since they generally show performance detriments when using explicit knowledge. Older adults would be expected to benefit from discovering how to perform the movement themselves as it would promote greater implicit learning.

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Appendix A

Edinburgh Handedness Inventory

Your participant ID: _____

Please indicate with a one (1) 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 a two (2).

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

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

Please stop here

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

Appendix B

File Number: H12-13-09

Date (mm/dd/yyyy): 01/11/2017



Université d'Ottawa **University of Ottawa**
 Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

Ethics Approval Notice
Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

<u>First Name</u>	<u>Last Name</u>	<u>Affiliation</u>	<u>Role</u>
Erin K.	Cressman	Health Sciences / Human Kinetics	Supervisor
Mohammad	Abu-Shaabn	Health Sciences / Human Kinetics	Student Researcher
Jean-Michel	Bouchard	Health Sciences / Human Kinetics	Student Researcher
Stefan	Maksimovic	Health Sciences / Human Kinetics	Student Researcher
Kristin-Marie	Neville	Health Sciences / Human Kinetics	Student Researcher

File Number: H12-13-09

Type of Project: 4th year

Title: Motor Adaption and sensory recalibration

Renewal Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
03/12/2016	03/11/2017	Renewal

Special Conditions / Comments:
 N/A

File Number: H12-13-09

Date (mm/dd/yyyy): 01/11/2017



Université d'Ottawa **University of Ottawa**
 Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

This is to confirm that the University of Ottawa Research Ethics Board identified above, which operates in accordance with the Tri-Council Policy Statement (2010) and other applicable laws and regulations in Ontario, has examined and approved the ethics application for the above named research project. Ethics approval is valid for the period indicated above and subject to the conditions listed in the section entitled "Special Conditions / Comments".

During the course of the project, the protocol may not be modified without prior written approval from the REB except when necessary to remove participants from immediate endangerment or when the modification(s) pertain to only administrative or logistical components of the project (e.g., change of telephone number). Investigators must also promptly alert the REB of any changes which increase the risk to participant(s), any changes which 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 and safety of the participant(s). Modifications to the project, including consent and recruitment documentation, should be submitted to the Ethics Office for approval using the "Modification to research project" form available at: <http://research.uottawa.ca/ethics/submissions-and-reviews>.

Please submit an annual report to the Ethics Office four weeks before the above-referenced expiry date to request a renewal of this ethics approval. To close the file, a final report must be submitted. These documents can be found at: <http://research.uottawa.ca/ethics/submissions-and-reviews>.

If you have any questions, please do not hesitate to contact the Ethics Office at extension 5387 or by e-mail at: ethics@uOttawa.ca.

Appendix C

Background information and consent form

Motor adaptation and sensory recalibration

Supervisor: Dr. Erin Cressman,
Assistant Professor,
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School of Human Kinetics, University of Ottawa
Ottawa, Ontario, K1N 6N5

Principal Investigator:

Kristin-Marie Neville, M. Sc Student, School of Human Kinetics, University of Ottawa

Stefan Maksimovic, M. Sc Student, School of Human Kinetics, University of Ottawa

Mohammad Abu-Shaaban, 4th year Undergraduate Research Project Student, School of Human Kinetics, University of Ottawa

Jean-Michel Bouchard, 4th year Undergraduate Research Project Student, School of Human Kinetics, University of Ottawa

Funding: National Science and Engineering Research Council (NSERC)

Background

Most of us perform goal directed actions – i.e. reaching for a cup of coffee – without thought or effort. It is only after something goes wrong (i.e. damage to part of the brain), that we begin to appreciate how complex a job the brain has in transforming sensory signals (e.g. visual input) into appropriate action plans. The overall goal of the research being undertaken in my laboratory is to understand how the brain transforms sensory input into motor output in the “healthy” brain. This research has important implications for people suffering from neurological disorders, as it is only after we gain a fundamental understanding of the normal mechanisms underlying goal directed action that we can begin to design effective rehabilitation programs, targeted at individuals with damage to certain areas of the brain.

Purpose

The purpose of this research is to determine how the brain combines multiple sources of sensory information so that it can plan an appropriate movement and form a coherent estimate of where the limb is in space. In particular, we are looking at the integration of visual and proprioceptive information in the brain, where proprioceptive input arises from sensory receptors inside the body that enable us to localize various parts of the body in relation to each

other (e.g. proprioception is the sense that allows you to touch your index finger to your nose when your eyes are closed).

Subject Profile

To be a participant you must be a right-handed, healthy (no history of neurological, and/or motor dysfunction) adult with normal or corrected-to-normal visual function, aged between 16 and 40 years.

Study Procedures

In order to examine how visual and proprioceptive inputs are integrated in the brain you will be asked to point to targets (i.e. a visual dot) with your right/left hand and indicate where your hand is relative to a target (i.e. left or right). Your task will be to move and report your position as accurately as possible to the target. In order to record your hand movement, you will hold onto a robot handle (KINARM, Kingston, ON, Canada). We do not need to do any preparation of the skin. It is important to note that this robot system only captures the position of the handle (it does not capture your image (i.e. personal features) in any form).

Experimental Session

The entire experiment will be completed in Room 403 in Montpetit Hall. Each participant will complete the experiment either during a single testing session or during testing sessions on 5 consecutive days. Each testing session will range from 30 minutes up to a maximum of 2 hours. Thus, participants volunteering in the extended training groups will be devoting a maximum of 10 hours in total to this study across 5 consecutive days. Upon completion of the testing session(s) the experimenter will provide additional details on the visual information displayed and the hypothesized results.

Risks and Discomforts

The risks involved in participating in this experiment are minimal. That is, the risks are no greater than the risks experienced in everyday life. However, you might experience slight fatigue, as you will be asked to maintain focused attention throughout the experiment and perform multiple reaching movements. In attempt to ensure that you do not become fatigued, we have scheduled 5 minute breaks approximately every 15 minutes. As well, please let us know if you require longer or more frequent periods of rest.

Benefits

Thank you for taking the time to participate in this study. While there are no direct benefits to you from participating in this study, this research has important implications for people suffering from neurological disorders. It is only after we gain a fundamental understanding of the normal mechanisms underlying sensory guided action that we can begin to design effective rehabilitation programs, targeted at individuals with damage to certain areas of the brain.

Anonymity and Confidentiality

All information and data collected are coded to maintain confidentiality. Specifically, raw data will be stored using an alphanumeric coding system so that no one will be able to identify you as your name will not appear on these files. The data will be analyzed on password protected computers that only the researchers directly involved in this study will have access to. Once analyzed the data will be kept in Room 403, Montpetit Hall, in locked filing cabinets and only the researchers directly involved in this study will have access to your data.

No records bearing your name will leave the institution. You are encouraged to request and discuss the results of the experimental trials at any time.

The data collected in this study may be published in scientific journals, as well as in a University of Ottawa MSc thesis. The data will be kept for a period of 10 years post-publication and will subsequently be destroyed by the physical resources service of the University of Ottawa.

Voluntary Participation

For the entire duration of the study, it is fully understood that you may refuse to participate or withdraw from the study at any time, without question. As well, you can ask the researcher any questions about any part of the research being conducted at any time. Data of participants who withdraw from the study will be destroyed immediately.

INFORMED CONSENT OF PARTICIPANT

Research involving human subject require written consent of the participants.

I, _____, hereby volunteer to participate as a subject in the study entitled “**Motor adaptation and sensory recalibration**”. I have read the information presented in the above background information and I had the opportunity to ask questions to the investigators. I understand that my participation in this study, or indeed any research, may involve risks that are currently unforeseen.

I recognize that there will be no direct benefit to me from my participation in this study.

I understand that if I have any questions regarding the study, I may contact Dr. Erin Cressman at 613-562-5800 ext 4264. If I have any questions or complaints with regards to the ethical conduct of this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON K1N 6N5, tel.: 613-562-5387, email: ethics@uottawa.ca .

I have been given a copy of this Background Letter and Consent Form for me to keep.

Signature of participant: _____ Date: _____

Signature of Researcher: _____ Date: _____

Research Summary/Debriefing text

The overall goals of this research is to examine the influence of implicit and explicit contributions to motor adaptation.

Thus, the specific goal of this experiment was to look at the ability of awareness of distorted visual feedback (as influenced by instruction and distortion magnitude) to influence motor performance. To examine this, we had you reach to targets when provided with false visual feedback of the hand (e.g. reaching to a target while seeing a cursor that was rotated with respect to the hand's actual location). We then had you reach to targets without any feedback to assess motor learning/adaptation. Your results from the motor tasks will be compared in order to determine the influence of awareness on motor adaptation.

After having been briefed on the purpose of this research, do you consent to have your data included in this study?

Signature of participant: _____ Date: _____

Signature of Researcher: _____ Date: _____