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Visuomotor Rotation Adaptation and Workspace Manipulation: A Behavioral and Cognitive Emphasis

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VISUOMOTOR ROTATION ADAPTATION AND WORKSPACE MANIPULATION: A BEHAVIORAL AND COGNITIVE EMPHASIS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Kinesiology

by
Reuben N. Addison
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NOMENCLATURE

NJ – Normalized Jerk

ARV – Average resultant velocity

PL- Path length

IDE – Initial direction error

MT – Movement time

RT – Reaction time

RST – Response time

LLL – Left-left-left

RRR – Right-right-right

LRL – Left-right-left

RLR – Right-left-right

EEG–Electroencephalography

ERP–Event-Related Potentials

LSU–Louisiana State University

CTL – Contralateral workspace

IPS – Ipsilateral workspace

CEN – Central workspace

VIS - Visible target

REM – Remembered target

ABSTRACT

This is a three-study dissertation in which we aimed to broaden our knowledge of the mechanisms contributing to a 45° clockwise visuomotor adaptation by including variations in workspace. We provide behavioral and in one study physiological outcomes as evidence to support our conclusions. In the first experiment, we observed the adaptation of movement parameters such as pathlength, movement time, resultant velocity, and normalized jerk across groups trained with rotated visual feedback with both the left and right hands. Workspace location and hand differentially affected movement trajectory length. The group that practiced the task with their nondominant, left hand showed larger after-effects, thus deviations in pathlength and initial direction error than those who practiced with their right hand. We also observed the transfer of pathlength from the left to the right hand but no ensuing after-effects. These findings failed to support the dynamic dominance model of bilateral transfer asymmetry, which posits the right hand is uniquely adapted for movement trajectory information. In the second experiment, participants adapted to the visuomotor rotation and generalized the adaptation to other workspaces. Subjects adapted to the visuomotor rotation in all three workspace locations. Corresponding neural measures indicated workspace related changes, with the biggest differences between contralateral and ipsilateral workspaces consistent with the observed behavioral results. The observed neurophysiological patterns were mainly in the right central and parietal–cortical areas involved in spatial processing. We argue these brain areas may be involved in workspace-related inhibition to allow the left hemisphere work efficiently. In the final experiment we investigated how manipulation of visual feedback and workspace location affected visuomotor adaptation for groups using real and remembered targets during performance. We showed participants visuomotor rotation transferred from the central to the

ipsilateral workspace location. Also removing the target during rotational adaptation decreased, thus improved reaction time for unrotated real target trials regardless of workspace. Since gaze strategies differed between groups, we reasoned that gaze does not significantly contribute to visuomotor adaptation. The current studies add to existing evidence for understanding mechanisms responsible for adapting to a visuomotor rotation under different contexts.

CHAPTER 1. INTRODUCTION AND SIGNIFICANCE

A critical aspect of human movement is constantly adapting movements to new situational demands such as learning to perform goal-directed tasks with a prosthetic limb or using telerobotics to remotely execute basic motor tasks like maneuvering surgical equipment. We learn to adapt our everyday activities to perform in a systematically changed environment. Researchers use visuomotor adaptation paradigms which utilized visual perturbations such as a change of visual feedback of the movement applying an angular vector and/or gain change (i.e., reduction or increase of movement extent) (Tseng, Diedrichsen, Krakauer, Shadmehr, & Bastian, 2007; Wolpert & Miall, 1996). Specific goal-oriented aspects of a motor task such as movement endpoint predictions (Feldman & Latash, 2005; Feldman, Ostry, Levin, Gribble, & Mitnitski, 1998), distance estimates (Gordon & Ghez, 1987), and hand position (Desmurget, Pelisson, Rossetti, & Prablanc, 1998) are preplanned. However, successful adaptation in these instances occurs when movement errors from visual feedback are used to influence limb proprioception and make adjustments from trial to trial (Rand & Heuer, 2019).

A visuomotor adaptation task is a type of sensorimotor learning task (e.g., Cunningham, 1989; Krakauer, 2009) that provides insights into how we interact with our environment, from planning to execution of movements (Seidler, 2010). Successful adaptation to produce the desired movement occurs when there is a match between the transformed visual coordinates (Vetter, Goodbody, & Wolpert, 1999) and the limb configuration relative to the target location as shown in figure 1.1 (Wang & Sainburg, 2005). The visuomotor system (i.e., a network that receives and integrates sensory inputs into a motor plan to execute movements) is responsible for the described

adaptation to perturbations such as rotations (Sarlegna & Sainburg, 2009).

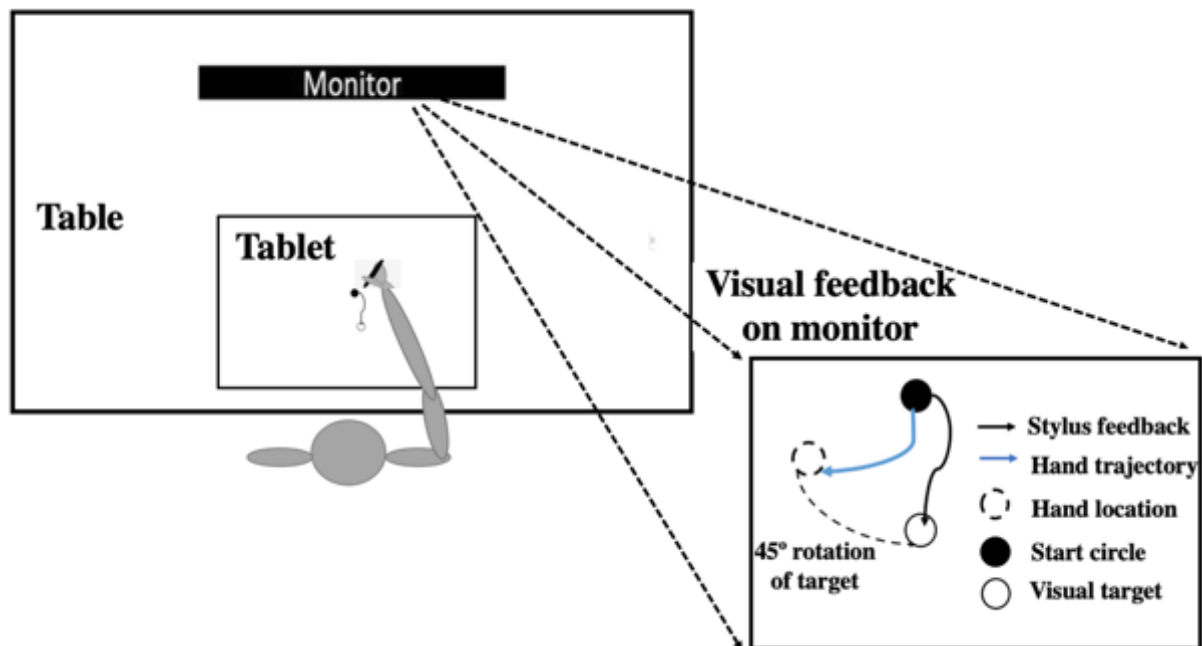


Figure 1.1. Visuomotor adaptation task

The participants are instructed to draw a straight line from the start location (black circle) to peripheral circles (open circle) equidistant from the start circle. When the participant moves the stylus toward the target (posterior in this case), a rotational offset is applied to the visual feedback of hand movement direction. For the posterior movement example, the participant would see the target actually move 45° to the left of the desired direction (see blue arrow in insert). The participant must move 45° to the right to counteract the applied offset.

CHAPTER 2. REVIEW OF LITERATURE

Introduction

The purpose of this section is to review studies on visuomotor adaptation, workspace effects, and visual encoding of reach target during visuomotor adaptation. The section begins with the competing studies of workspace effects of adaptation and possible mechanisms responsible for the disparities in the results. The review included information about the role of vision and stabilization of visual percepts when making reaching movements during adaption. The section ends with the visual coding of reach targets.

Adaptation across limbs

Researchers investigating the generalization of a visuomotor adaptation task between limbs used across workspaces indicate conflicting results (Sainburg & Wang, 2002; Wang & Sainburg, 2006; Wang, 2008). For instance, in the central workspace, an asymmetric generalization of movement parameters such as initial direction and endpoint accuracy during a visuomotor task occurred between hands, consistent with the dynamic dominance model (Sainburg & Wang, 2002). According to the dynamic dominance model, motor asymmetry of the hand results from the control asymmetry of the two cerebral hemispheres, with each uniquely adapted to different aspects of movement control (Sainburg & Wang, 2002; Wang & Sainburg, 2004, 2006). The dominant hemisphere is responsible for directional information such as the initial direction of the movement, movement trajectory, and movement speed, whereas the non-dominant hemisphere is responsible for movement endpoint accuracy among right-handed people (Pan & Van Gemmert, 2013; Wang & Sainburg, 2004, 2006). In the ipsilateral workspace

location, the pattern of transfer generalization between hands was symmetric, failing to support the dynamic dominance model (Wang & Sainburg, 2006). There was also a lack of adaptation and generalization when the vertically presented visual feedback space differed from the horizontal task workspace, whether in central or ipsilateral locations (Wang 2008). In contrast, Pan and van Gemmert (2013a) reported adaptation with generalization in the central workspace consistent with the dynamic dominance model despite the same use of separate visual feedback space and task workspaces. Clearly, the application of the dynamic dominance model seems inconsistent with different workspace set-ups.

Adaptation across workspace

Researchers also studied visuomotor adaptation and its generalization across different workspaces (Heuer & Hegele, 2011; Krakauer, Pine, Ghilardi, & Ghez, 2000; Thomas & Bock, 2012; Vetter et al., 1999; Woolley, Tresilian, Carson, & Riek, 2007) and obtained varied results. While some researchers determined adaptation effects on workspace to indicate visuomotor adaptation may be workspace specific (Thomas & Bock, 2012; Woolley et al., 2007), others reveal contrary results to indicate adaptation can take place in different workspaces (Heuer & Hegele, 2011; Krakauer et al., 2000; Vetter et al., 1999). Multiple possible explanations exist for the varied results in the studies above, such as prior knowledge (Miall, 2002), the direction of movement (Pearson, Krakauer, & Mazzoni, 2010), arm posture at the start of movement (Gandolfo, Mussa-Ivaldi, Bizzi, Gandolfo, & Gandolfo, 1996; Ghahramani & Wolpert, 1997), the position of the target (Woolley et al., 2007), or the order of target presentation (Welch, Bridgeman, Anand, & Browman, 1993). Conditions corresponding to workspace specific and

nonspecific adaptations can offer greater insight into understanding control of visuomotor adaptations.

Role of vision in visuomotor control

Visuomotor adaptation takes place in an extrinsic space within the environment. The motor system relies on visual information to encode the spatial features of the environment (i.e., target location) for movement control in a visuomotor adaptation task (Sarlegna & Sainburg, 2009). Our perception of the spatial structure of the physical environment is represented either as observer-centred (egocentric) or environment-centred/external reference (allocentric) (Thaler & Todd, 2010). Eye movements can play an integral part of successful planning and/or performance of various visuomotor tasks, thus are important to such control.

Stabilizing visual perception

Reaching and pointing movements to visual targets are often accompanied by saccades (Gribble, Everling, Ford, & Mattar, 2002). Saccades are quick eye repositioning movements that stabilize visual percept (Ross, Morrone, Goldberg, & Burr, 2001). Saccades can be voluntary or initiated more automatically by an abrupt change in the visual field (Gremmler & Lappe, 2017). The speed involved in saccadic movements temporarily blurs the image, resulting in saccadic suppression (Ross et al., 2001). During saccadic suppression the cortex obstructs visual processing, resulting in visual instability and minimizing impact on visual inputs (Campbell & Wurtz, 1978) used for visuomotor control.

Another visual mechanism for stabilizing visual percept is the smooth pursuit system, responsible for visual tracking of moving objects (Blohm & Lefevre, 2010). Tracking a movement trajectory with the eyes during goal-directed reaching using smooth pursuit helps

maintain visual tracking accuracy (Lisberger, 2010; Ono, 2013), as smooth pursuit eye movements reach lower peak speeds than saccades (Buonocore, Skinner, & Hafed, 2019), thus eliminating the blur. Despite the differences between the saccades and smooth pursuit, Krauzlis (2004) reported that both share similar neural inputs, to help explain their combined use during some visual tracking tasks. Although position of objects on the retina drive visually induced saccades (Kosovicheva, Wolfe, & Whitney, 2014) target velocity, acceleration and position on the retina are the main drivers of smooth pursuit (Ilg & Thier, 2008; Krauzlis, 2004; Lisberger, 2010). The moving target causes a slip of the image motion on the retina decreasing visual acuity, and smooth pursuit responds by reducing the velocity of the retinal slip (Missal & Heinen, 2017) to stabilize the image. Overall, both saccadic suppression and smooth pursuit are two mechanisms by which we create a stable representation of physical space through vision, a crucial component in performing goal-directed tasks.

Eye movements during visuomotor rotation task

People typically fixate a target during goal-directed reaches (Rentsch & Rand, 2014) which helps planning and improves movement control precision (Abrams, Meyer, & Kornblum, 1990; Prablanc, Echallier, Jeannerod, & Komilis, 1979). Gaze patterns play a significant role in planning ongoing movement toward the target (Gaveau et al., 2008; Prablanc, Pelisson, & Goodale, 1986), as in estimating the time to reach the target (Bowman, Johansson, & Flanagan, 2009; Johansson, Westling, Backstrom, & Flanagan, 2001), as well as termination of movement, as in confirming its completion (Rand, 2014; Rand & Stelmach, 2010). Thus, gaze is used to update movement plans for improved movement control during the ballistic (~80ms of movement onset) and corrective (>80ms) phases of movement (Abrams et al., 1990; Prablanc et al., 1979).

Moreover, after a visual perturbation, such as rotated visual feedback of hand position, gaze corresponds to cursor movement (position of the hand) in the early stages of learning then transfers to the target later in learning (Rentsch & Rand, 2014). Clearly, people may use a combination of fixation, saccades, and/or smooth pursuit eye movements when learning visuomotor rotational tasks.

Gaze-centered spatial coding of visual reach target during visuomotor adaptation

During a visuomotor rotation adaptation task, the typical pattern of eye movements - tracking the trajectory of hand movements at the early stages and later fixating on the target (Rand & Rentsch, 2016, 2017; Rentsch & Rand, 2014) differs slightly depending on the position of the target in the hemispace (Rand & Rentsch, 2017). Rand and Rentsch (2017) compared gaze patterns during visuomotor adaptation task under two different hemispaces conditions: ipsilateral and contralateral. They noted that the typical gaze behavior of fixating on a target after target presentation was delayed for contralateral target space.

Gaze characteristics also depend on the kind of visual feedback available in a visuomotor adaptation task. For example, end-point visual feedback or continuous feedback of movement trajectory and end-point visual feedback differ (Rand & Rentsch, 2016). Researchers studied adaptive gaze behavior under a free gaze condition with continuous visual feedback and observed gaze was directed at the cursor representation of hand movements at the early stages and later fixated on the target (Rentsch & Rand, 2014). However, when visual feedback was limited to endpoint, people changed gaze direction from the visual endpoint target to the hand at the end of reaching (Rand & Rentsch, 2016). Continuous visual feedback compared to terminal feedback during visuomotor adaptation led to shorter reaction time (Hinder, Riek, Tresilian, de Rugy, &

Carson, 2010; Hinder, Woolley, Tresilian, Riek, & Carson, 2008), longer movement time (Hinder et al., 2010; Hinder et al., 2008; Shabbott & Sainburg, 2010) and higher precision of reaches (Shabbott & Sainburg, 2010).

Summary & Literature gap

In previous studies, researchers investigated whether adaptation to a visuomotor task could generalize to other workspace locations (Heuer & Hegele, 2011; Krakauer et al., 2000; Thomas & Bock, 2012; Vetter et al., 1999; Woolley et al., 2007) and/or the opposite limb (Pan & van Gemmert, 2013a). While some studies reveal transfer of motor plan from one workspace to another (Heuer & Hegele, 2011; Krakauer et al., 2000; Vetter et al., 1999), others do not (Thomas & Bock, 2012; Woolley et al., 2007). One possible reason for conflicting findings involves deviations in parameters reported. Initial directional error, often used to assess adaptation, may not completely describe adaptation. The conflicts may also result from differences in gaze adaptive behavior and methodologies used during visuomotor adaptation performance. The following studies were designed to account for these potential discrepancies and offer insight into workspace and gaze direction use during visuomotor adaptation tasks. Visuomotor adaptation tasks are not limited to a single workspace location. Understanding the strategies that contribute to successful adaptation under different contexts will help implement effective strategies in real-life applications of visuomotor adaptation tasks.

CHAPTER 3. VISUOMOTOR ADAPTION ACROSS LIMBS AND WORKSPACE LOCATIONS

Introduction

Visuomotor adaptation tasks are goal-directed motor tasks designed to understand how individuals interact with their environment. They include the need to plan movement trajectories for the execution of the desired action (Seidler, 2010). Bilateral transfer of learning generalizes learning (and/or adaptation) of a motor task across the arms and/or legs (Pan & Van Gemmert, 2013; Sainburg & Wang, 2002; Wang & Sainburg, 2006). It often involves asymmetric transfer, i.e., the strength of the transfer differs across the arms and/or legs (Sainburg & Wang, 2002; Wang & Sainburg, 2004, 2006). The dynamic dominance model explains this asymmetry between the arms as differences of the arm controllers adapted uniquely to distinct features of movement performance. According to the model the dominant arm responsibility involves control of intersegmental dynamics specifying directional information and shape while the non-dominant arm involves control of final posture specifying movement endpoint accuracy (Sainburg & Wang, 2002; Wang & Sainburg, 2004, 2006).

Some researchers showed a pattern of asymmetry in bilateral transfer of visuomotor adaptation within the central workspace location (Pan & Van Gemmert, 2013; Sainburg, 2002). Another study revealed a symmetric pattern of transfer, inconsistent with the asymmetric pattern suggested by the dynamic dominance model when the workspace was located lateral to the shoulders of the subjects (Wang & Sainburg, 2006). In this case, the visual feedback appeared in the same plane as the surface on which the arm was moving (i.e., horizontal plane). However, when the visual and motor workspace were physically separated, adaptation was not observed in

either the central or ipsilateral workspace (Wang, 2008). The differences in the set-up of motor and visual workspace possibly resulted in conflicting findings between studies. Whether these reported inconsistencies of findings between studies stem from differences in workspace manipulations, the inherent task constraint differences (e.g., task difficulty), or both remain unanswered.

Spatial representations of target location during visuomotor control can be affected by features of the physical workspace environment. The separation of the visual and hand workspaces can subsequently affect how reaches toward targets are planned and executed (Beurze, Van Pelt, & Medendorp, 2006; Blangero et al., 2007; Dijkerman & Milner, 1998; Khan, Pisella, Rossetti, Vighetto, & Crawford, 2005). Various studies employed on bimanual transfer which include different workspace manipulations may have led to contrasting findings. We decided to combine the manipulation of workspace and transfer conditions to investigate workspace manipulation effects on the symmetry of transfer across the upper limbs in a single experiment. Thus, the primary goal of this study was to gain a better understanding of the mechanisms responsible for adaptation and its generalization across limbs acting in the different workspace locations. One unique aspect of the present study involved the inclusion of three workspace configurations within two experiments utilizing both the same single experimental protocol and task. Based on previous work (Pan & van Gemmert, 2013a; Wang & Sainburg, 2006), we predicted that movement parameters will show 1) an asymmetric pattern of transfer in the central workspace consistent with the dynamic dominance model, and 2) that these asymmetric patterns of transfer will disappear and become a symmetric pattern of transfer when the workspace of the arm is changed to the ipsilateral and contralateral spaces. A symmetric

pattern of transfer in the ipsilateral and contralateral workspace locations would be inconsistent with the dynamic dominance model suggesting specificity of workspace location for the pattern of bilateral transfer across limbs as shown by Wang (2008) in the ipsilateral workspace location. To address these hypotheses two experiments were designed (see Figure 3.1).

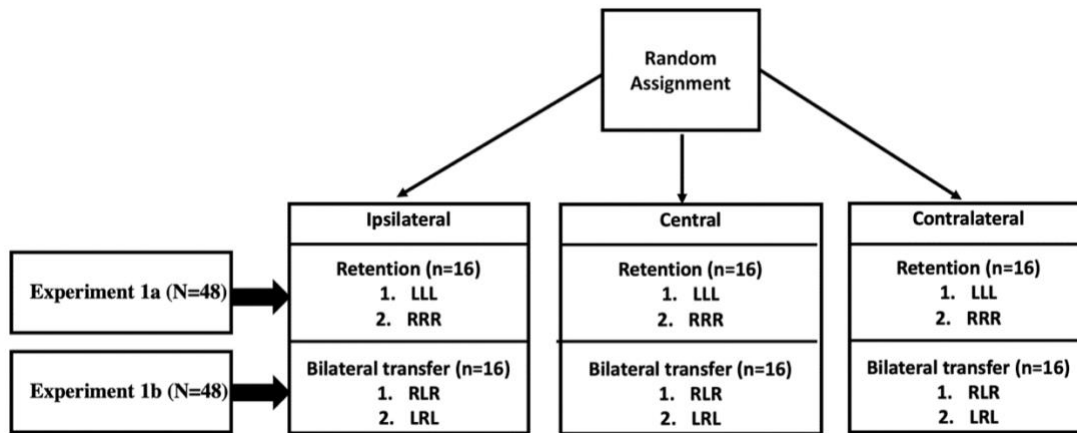


Figure 3.1. Experimental set up for each experiment

In Experiment 1a, assessments and training were in the same space using the same hand; either the nondominant (LLL) or dominant (RRR). In Experiment 1b, the hand used for assessments differed from the hand used for training; either RLR or LRL. R = dominant right hand; L = nondominant left hand.

Experiment 1a

In experiment 1a (retention), participants were randomly assigned to one of 3 groups each performing training and retention test in one of three movement workspaces. Each workspace condition was performed by participants divided into two distinct sub-groups; one sub-group

performed the pretest, training, and post-test with their non-dominant hand (LLL) and the other sub-group performed the task with their dominant hand (RRR).

Methods for experiment 1a

Participants: Forty-eight young adults (Mean: 20.58 years, 18-26 years old, including 37 females) with normal or corrected-to-normal vision participated in the study. Participants were randomly assigned to one of three experimental groups with each group divided into 2 sub-groups. All participants were right-hand dominant according to the Edinburgh Handedness Inventory (Oldfield, 1971) and had a laterality quotient of 0.6 or higher. We communicated the purpose of the study to all participants before asking them to sign the consent form prior to the study. The experimental protocol was approved by the Institutional Review Board for Human Subjects Research at Louisiana State University.

Groups: The six groups were divided across the three location conditions of placement of the tablet. The first two out of the six groups performed all training trials in the workspace between the two shoulders (Central). The second two groups performed all training trials of the task in the workspace on the outside of the shoulder of the hand holding the pen (ipsilateral). The last two groups performed all training trials of the task in the workspace on the outside of the shoulder opposite to the hand holding the pen (contralateral). For each set of two groups within each workspace location, one performed the task with the left hand and the other with the right hand. Baseline, retention, and after-effects assessments were performed for all groups within the same location condition of placement of the tablet as trained.

Equipment: A normal looking electronic non-inking pen (WACOM ZP-130) was used to make drawings on a digitizer tablet. The digitizer tablet (WACOM Intuous3 12x19) connected to a PC recorded pen movements which were visually presented on an attached monitor (50x30cm). The X- and Y- position of pen tip was sampled with a frequency of 200Hz and spatial resolution of 0.0005 cm.

Setup and Task instructions: The monitor was situated in front of the seated participants; however, the location of the tablet positioned in the horizontal plane was moved depending on the condition (Figure 3.2). Participants were instructed to move the digital pen over the tablet. The pen tip of the digital pen was shown in real-time as a cursor on a vertically oriented monitor placed centrally in front of the participants. They were asked to move the pen from a start position (a black circle in the center of the monitor; 0.5 cm diameter) to one of 4 target positions (a black circle 2.5 cm away from the start position; 0.5 cm diameter) without lifting the pen, effectively drawing a line segment. After the start circle appeared, the participants were instructed to move the cursor within the start circle. After the cursor entered the start circle, the start circle disappeared while the target circle appeared. At this time, participants were asked to move the pen as fast and as accurately as possible to the target using a single aiming movement. Targets were located either 2.5cm above, below, to the right, or to the left of the start position. Table 3.2 shows the experimental progression of the 64 trials and whether the online visual feedback of the movement trajectory was unrotated or rotated 45° clockwise.

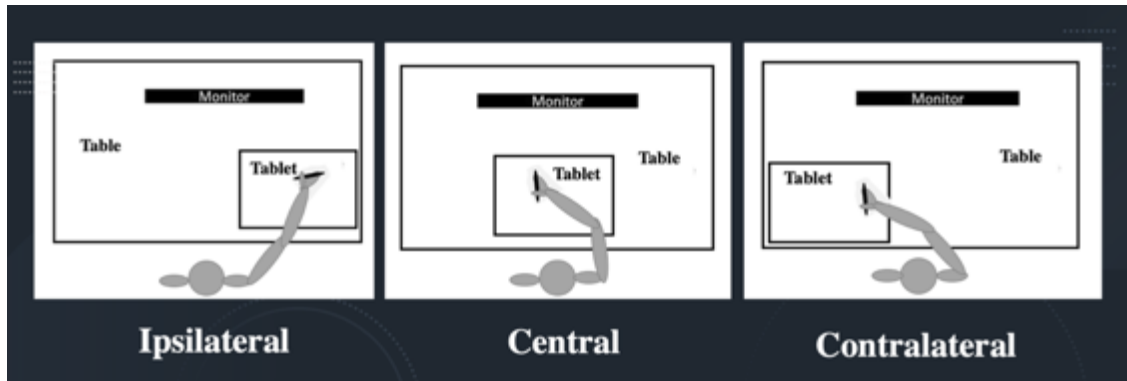


Figure 3.2. Workspace location manipulation

Participants viewed the cursor motion on a vertically oriented monitor. The cursor movement corresponded to movement of the electronic pen on the horizontal oriented tablet. Note the workspace is located ipsilateral to the performing upper limb (left panel), central to the body midline (middle panel), or contralateral to the performing upper limb (right panel). Note: The figure shows only the setup for the three groups performing with the right hand, an additional 3 groups (not shown) were performing with the left hand, in which the setup mirrors the setup for the groups performing with the right hand.

Table 3.1. Experimental progression for experiment 1a

Group	Pre-test unrotated (8 Trials)	Pre-test rotated (8 Trials)	Training rotated (40 Trials)	Post-test rotated (8 Trials)	Post-test unrotated (8 Trials)
RRR	R	R	R	R	R
LLL	L	L	L	L	L

R = used right hand; L = used left hand

Procedure: Participants first performed a few familiarization trials to get acquainted with the setup and equipment. In the familiarization task the distance between the center circle and the targets was 2cm instead of the 2.5cm distance used during the experimental conditions. Also the diameter of the start and target circles were 1cm during familiarization instead of 0.5cm diameter of the circles used during the experimental conditions to avoid learning effects. After participants were familiar with the setup and equipment the experiment was started. The experimental protocol of trial progression for each group was followed (Table 3.2). The baseline sessions before training included performance without and with rotation of visual feedback. The participants performed the training trials with feedback rotation followed by a post-training session with rotated feedback and a session with unrotated feedback. Performance changes from the unrotated baseline session to the post-training session with unrotated feedback determined aftereffects, while performance differences between the rotated baseline and the rotated post-training session determined retention.

Data processing: The pen tip data recordings were processed with a custom program developed in MATLAB (MathWorks Inc., Natick, MA, USA) (e.g., Pan & van Gemmert, 2013). The position signals were filtered using a Butterworth 4th order dual pass filter with a cut-off frequency of 16 Hz. The movement segments were parsed using the 5% of the peak velocity criterion in the velocity profile to determine movement onset (i.e., start) and offset (i.e., end).

Dependent Variables

The dependent variables were calculated as follows:

- Initial direction error-IDE (degrees): the angle between the vector from the center of the home circle position and the center of target position and the vector between the onset location of the movement and the location at 80 ms into movement.
- Movement time-MT (s): The stroke duration between the onset and offset of the movement.
- Pathlength-PL (cm): Cumulative length of the movement trajectory between onset and offset of the movement.
- Normalized jerk-NJ (unitless): The rate of change of acceleration normalized for stroke size and duration (cf. Van Gemmert, Teulings, & Stelmach, 1998).
- Resultant velocity-RV (cm/s): Square root of the sum of the squared velocity in the x- and y-direction between onset and offset of the movement.

Statistical analysis: All data were checked for normal distribution using a Shapiro-Wilk's test. The data were skewed; therefore, the median scores of the dependent variables of the pre-test (unrotated and rotated) and post-training sessions were determined. These medians were entered into two separate mixed factors ANOVAs (Retention and After-effects were analyzed separately, see Table 3.2) with 3 Workspace (Central, Ipsilateral, Contralateral) and 2 Hand (Left, Right) conditions as the between-subjects factors, and 2 Test (pre-test, post-test) conditions as the within-subjects factor. If the main effect of workspace or any interaction proved significant, Bonferroni corrected Post-hoc tests were used to determine differences between conditions and/or groups. The significance level was set at alpha is 0.05.

Results – Experiment 1a

The results revealed a significant main effect of Test for PL (post-test - pre-test = -0.35 cm, $F_{(1,42)} = 30.991$, $p < 0.05$; $\eta^2 = 0.48$), MT (post-test - pre-test = -504.48 ms, $F_{(1,42)} = 69.610$, $p < 0.05$; $\eta^2 = 0.63$), RV (post-test - pre-test = 0.41 cm/s, $F_{(1,42)} = 40.872$, $p < 0.05$; $\eta^2 = 0.48$), and NJ (post-test - pre-test = -1299.29, $F_{(1,42)} = 25.883$, $p < 0.05$; $\eta^2 = 0.40$) but IDE failed to reach significance (post-test - pre-test = -1.634°, $F_{(1,42)} = 3.85$, $p > 0.05$; $\eta^2 = 0.03$). There was significant reduction of movement trajectory length (Figure 3.3), participants moved toward the target significantly faster (Figure 3.4 & 3.5) and smoother (Figure 3.6) from pre-test to post testing. There was no Group effect on all variables, i.e., PL (LLL - RRR = 0.1 cm, $p > 0.05$; $\eta^2 = 0.02$), MT (LLL - RRR = 74.48 ms, $p > 0.05$; $\eta^2 = 0.01$), RV (LLL - RRR = -0.06 cm/s, $p > 0.05$; $\eta^2 = 0.00$), NJ (LLL - RRR = -197.50, $p > 0.05$; $\eta^2 = 0.02$) and IDE (LLL - RRR = 0.23°, $p > 0.05$; $\eta^2 = 0.00$). There were also no main effects of Workspace on PL ($p > 0.05$; $\eta^2 = 0.09$), MT ($p > 0.05$; $\eta^2 = 0.03$), RV ($p > 0.05$; $\eta^2 = 0.07$), NJ ($p > 0.05$; $\eta^2 = 0.10$), and initial directional error ($p > 0.05$; $\eta^2 = 0.02$). None of the two-way interactions showed significance, but a three-way interaction of Group, Workspace, and Test on PL (see Figure 3.3) proved significant ($F_{(2,42)} = 5.84$, $p < 0.05$; $\eta^2 = 0.22$). The Post-hoc tests showed a significant change (i.e., reduction) of PL at post-test for the group that practiced with their left hand (IPS-LLL) in the ipsilateral workspace (post-test - pre-test = -0.79 cm, $p < 0.05$; $\eta^2 = 0.43$) and the group that practiced with their right hand in the central (CEN-RRR) (post-test - pre-test = -0.38 cm, $p < 0.05$; $\eta^2 = 0.15$) and contralateral workspaces (CTL-RRR) (post-test - pre-test = -0.39 cm, $p < 0.05$; $\eta^2 = 0.16$), thus also contributing to the significant main effect of Test on PL (see Figure 3.3). Differences in PL from pre-test to post-test for the CEN-LLL (post-test - pre-test = -0.22 cm, $p > 0.05$; $\eta^2 = 0.06$),

CTL-LLL (post-test - pre-test = -0.21 cm, $p > 0.05$; $\eta^2 = 0.05$) and IPS-RRR (post-test - pre-test = -0.14 cm, $p > 0.05$; $\eta^2 = 0.02$) failed to reach significance.

After-effects

A significant main effect of Test on PL (post-test - pre-test = 0.07 cm, $F_{(1,42)} = 5.330$, $p < 0.05$; $\eta^2 = 0.11$), MT (post-test - pre-test = -196.46 ms, $F_{(1,42)} = 16.341$, $p < 0.05$; $\eta^2 = 0.28$), RV (post-test - pre-test = 0.28 cm/s, $F_{(1,42)} = 12.848$, $p < 0.05$; $\eta^2 = 0.23$), and NJ (post-test - pre-test = -621.7, $F_{(1,42)} = 18.790$, $p < 0.05$; $\eta^2 = 0.31$) and IDE (post-test - pre-test = 5.04°, $F_{(1,42)} = 10.112$, $p > 0.05$; $\eta^2 = 0.19$) were observed. Results for after-effects indicated movement took a longer PL and IDE increased after the bias was removed (see Figure 3.3). Movement toward the target was faster (Figure 3.4 & 3.5) and smoother (Figure 3.6). Group main effects were also observed for PL (LLL - RRR = 0.2 cm, $F_{(1,42)} = 20.961$, $p < 0.05$; $\eta^2 = 0.33$) and IDE ($F_{(1,42)} = 12.158$, $p < 0.05$; $\eta^2 = 0.22$). The LLL group recorded a greater PL (LLL - RRR = 0.2 cm) and IDE (LLL - RRR = 5.14°) than the RRR group. There were no effects of Group on MT (LLL - RRR = 220.94 ms, $p > 0.05$; $\eta^2 = 0.07$), RV (LLL - RRR = -0.05 cm/s, $p > 0.05$; $\eta^2 = 0.00$), and NJ (LLL - RRR = 309.41, $p > 0.05$; $\eta^2 = 0.04$). There were no main effects of Workspace on PL ($p > 0.05$; $\eta^2 = 0.05$), MT ($p > 0.05$; $\eta^2 = 0.11$), RV ($p > 0.05$; $\eta^2 = 0.11$), and directional error ($p > 0.05$). Only NJ ($F_{(2,42)} = 3.65$, $p < 0.05$; $\eta^2 = 0.15$) showed Workspace -related differences indicating differences in movement smoothness between workspaces. Post-hoc analysis showed a significant difference in NJ between the group that practiced in the contralateral workspace and the central workspace (CTL - CEN = 793.76, $p < 0.05$) but not between the group that practiced in the contralateral workspace and the ipsilateral (CTL - IPS = 614.75, $p > 0.05$) and between the central and ipsilateral workspace locations (CEN - IPS = -179.00, $p > 0.05$).

Participants who worked in the central workspace recorded smoother movements than those who worked in the contralateral workspace (see Figure 3.6). There was a two-way interaction between Group and Test on IDE ($F_{(1,42)} = 4.445$, $p < 0.05$; $\eta^2 = 0.10$). After-effects of IDE were observed only for the LLL group (post-test – pre-test = 8.39° , $p < 0.05$) but not for the RRR group (post-test – pre-test = 1.70° , $p < 0.05$). The three-way interaction showed no significance ($p > 0.05$).

Experiment 1b

In experiment 1b (bilateral transfer), participants were randomly assigned to one of 3 groups each performing training and retention test in one of three movement workspaces. Each workspace condition was performed by participants divided into two distinct sub-groups; i.e., one sub-group performed the pre-test and post-test with their non-dominant hand whereas training was with the dominant hand (LRL) and the other sub-group trained with their non-dominant hand and the pre-test and post-tests were performed with their dominant hand (RLR).

Methods for experiment 1b

Participants: Forty-eight young adults Mean age: 20.1 years, 18 -24 years old, including 37 females) with normal or corrected-to-normal vision participated in the study. Participants were randomly assigned to one of three experimental groups with each group divided into 2 sub-groups. All participants were right-hand dominant according to the Edinburgh Handedness Inventory (Oldfield, 1971) and had a laterality quotient of 0.6 or higher. We communicated the purpose of the study to all participants before asking them to sign the consent form prior to the study. The experimental protocol was approved by the Institutional Review Board for Human Subjects Research at Louisiana State University.

Procedure: The methods were similar to Experiment 1a, with six groups divided across the three locations of the tablet conditions. The difference is the hand used during pretest, training, and post-test varied—one group trained with the left hand and transferred to the right hand (RLR) and vice versa (LRL). Performance changes from the baseline unrotated session to the after-effects unrotated session showed acquisition effects, while baseline rotation to the post-test rotated session represented bilateral transfer. Baseline, retention, and after-effects assessments were performed for all groups within the same location condition of placement of the tablet as trained.

Table 3.2. Experimental progression for experiment 1b

Group	Pre-test unrotated (8 Trials)	Pre-test rotated (8 Trials)	Training rotated (40 Trials)	Post-test rotated (8 Trials)	Post-test unrotated (8 Trials)
LRL	L	L	R	L	L
RLR	R	R	L	R	R

R = used right hand; L = used left hand

Statistical analysis: All data were checked for normal distribution using a Shapiro-Wilk's test. The data was skewed; therefore, the median scores of the dependent variables of the pre-test (unrotated and rotated) and post-training sessions were determined. These medians were entered into two separate mixed factors ANOVAs (Transfer and After-effects were analyzed separately, see Table 2.1) with 3 Workspace (Central, Ipsilateral, Contralateral) and 2 Trained Hand (Left,

Right) conditions as the between-subjects factors, and 2 Test (pre-test, post-test session) conditions as the within-subjects factor. If the main effect of Workspace or any interaction proved significant, Bonferroni corrected Post-hoc tests were used to determine differences between conditions and/or groups. The significance level was set at alpha is 0.05.

Results - Experiment 1b

Our analysis indicated there were significant main effect of Test on PL (post-test - pre-test = -0.27 cm, $F_{(1,42)} = 14.724$, $p < 0.05$; $\eta^2 = 0.26$), MT (post-test - pre-test = -279.32 ms, $F_{(1,42)} = 17.232$, $p < 0.05$; $\eta^2 = 0.24$), and NJ (post-test - pre-test = -1126.19, $F_{(1,42)} = 16.101$, $p < 0.05$; $\eta^2 = 0.28$) but not RV (post-test - pre-test = 0.08 cm/s, $F_{(1,42)} = 2.154$, $p > 0.05$; $\eta^2 = 0.05$) and IDE (post-test - pre-test = -3.68°, $F_{(1,42)} = 2.62$, $p > 0.05$; $\eta^2 = 0.03$). There was a significant reduction of PL (Figure 3.3) in the untrained hand after training the opposite hand. Movement was faster (Figure 3.4) and smoother (Figure 3.6) in the opposite hand indicative on bilateral transfer to the untrained hand.

There was a significant main effect of Group on IDE (LRL - RLR = -5.57°, $F_{(1,42)} = 7.70$, $p < 0.05$; $\eta^2 = 0.16$). The RLR group recorded a higher directional error than the LRL group. PL (LRL - RLR = 0.12 cm, $F_{(1,42)} = 1.62$, $p > 0.05$; $\eta^2 = 0.04$), MT (LRL - RLR = 90 ms, $F_{(1,42)} = 0.35$, $p > 0.05$; $\eta^2 = 0.01$), RV (LRL - RLR = 0.00 cm/s, $F_{(1,42)} = 0.00$, $p > 0.05$; $\eta^2 = 0.00$) and NJ (LRL - RLR = -51.73, $F_{(1,42)} = 0.01$, $p > 0.05$; $\eta^2 = 0.00$) show no group effects. A significant main effect of Workspace on bilateral transfer was observed for MT ($F_{(2,42)} = 17.232$, $p < 0.05$; $\eta^2 = 0.45$), RV ($F_{(2,42)} = 10.473$, $p < 0.05$; $\eta^2 = 0.33$), and NJ ($F_{(2,42)} = 13.049$, $p < 0.05$; $\eta^2 = 0.38$) but not PL ($p > 0.05$; $\eta^2 = 0.01$) and directional error ($p > 0.05$; $\eta^2 = 0.01$). Post-hoc results also

revealed specific conditions where specific changes occurred across conditions. For instance, there was a significant change in MT between the group that practiced in the contralateral workspace and the central workspace (CTL - CEN = 1084.38 ms, $p < .05$) as well as the ipsilateral workspace (CTL - IPS = 724.45 ms, $p < .05$), there was no difference between the central and ipsilateral workspace conditions (CEN - IPS = -359.92 ms, $p > .05$). RV was lower among the group that practiced in the contralateral compared the groups that practiced in both the ipsilateral and central workspace location. NJ was significantly different between the groups that practiced the task in the contralateral workspace and the central workspace (CTL - CEN = 2832.91, $p < .05$) and the ipsilateral central workspace (CTL - IPS = 1790.41, $p < .05$), however there was no significant difference between the groups that practiced in the central and ipsilateral workspaces (CEN - IPS = -1042.51, $p > .05$). Movement was smoother for the groups that practiced in the central and ipsilateral workspace locations compared the groups that practiced in both the contralateral workspace location. There was a two-way interaction of Workspace and Test (pre/post-test) on MT ($F_{(2,42)} = 3.38$, $p < 0.05$; $\eta^2 = 0.14$) and NJ ($F_{(2,42)} = 3.74$, $p < 0.05$; $\eta^2 = 0.15$). MT was greater among the group that practiced in the contralateral compared the groups that practiced in both the ipsilateral and central workspace location. There was also a significant difference in RV between the group that practiced in contralateral workspace and the central workspace (CTL - CEN = -1.14 cm/s, $p < .05$) and ipsilateral workspaces (CTL - IPS = -0.735 cm/s, $p < .05$), there was however no difference between the groups that practiced in central and ipsilateral workspaces (CEN - IPS = 0.409 cm/s, $p > .05$). We also observed a two-way interaction effect of Groups and Test on PL ($F_{(1,42)} = 4.11$, $p < 0.05$; $\eta^2 = 0.11$). Post-hoc tests revealed the significant changes (i.e., reduction) of PL from pre-test to post- test was significantly

contributed by the RLR group (post-test - pre-test = -0.42, $p < .05$; $\eta^2 = 0.29$) but not the LRL group (post-test - pre-test = -0.13, $p > .05$; $\eta^2 = 0.04$) i.e., only the right hand benefited from the training of the left hand for PL, indicating bilateral transfer of PL occurred for the RLR group (See Figure 3.3). The observed main effects of Test for MT (post-test - pre-test = 556.56 ms, $p < 0.05$; $\eta^2 = 0.30$) and NJ (pre-test to post-test = -2201.23, $p < .05$; $\eta^2 = 0.33$) was significantly contributed by changes from pre-test to post-test of the named parameters in the contralateral workspace. There was no significant difference (i.e., reduction) in MT from baseline to post-test in the central (post-test - pre-test = 174.375 ms, $p > 0.05$; $\eta^2 = 0.04$) and ipsilateral (post-test - pre-test = 107.03 ms, $p > 0.05$; $\eta^2 = 0.02$) workspaces. There was also no significant difference (i.e., reduction) in NJ from baseline to post-test in the central (post-test - pre-test = 455.529, $p > 0.05$; $\eta^2 = 0.02$) and ipsilateral (post-test - pre-test = 721.82, $p > 0.05$; $\eta^2 = 0.05$) workspaces. Movement was significantly faster and smoother when using the untrained hand among the groups that practiced the task in the contralateral workspace location. Finally, we observed a significant two-way interaction between Group and Workspace on IDE ($F_{(2,42)} = 11.37$, $p < 0.05$; $\eta^2 = 0.35$). Post-hoc tests showed IDE was greater in the contralateral workspace compared to the ipsilateral workspace for the RLR group (CTL - IPS = 13.64°, $p < 0.05$). An opposite trend was observed for the LRL group (CTL - IPS = -8.78°, $p < 0.05$). IDE was greater in the central compared to the ipsilateral workspace for the RLR group (CEN - IPS = 11.16°, $p < 0.05$). There were no workspace-related differences of IDE between the contralateral and central (CTL - CEN = -2.88°, $p > 0.05$) as well as between the central and ipsilateral workspaces (CEN - IPS = -5.91°, $p > 0.05$) for the LRL group. There also no differences between the contralateral and central workspace for the RLR group (CTL - CEN = 2.48°, $p > 0.05$).

After-effects

Results for after-effects indicated a significant main effect for Test (post-test - pre-test-test adaptation) on MT (post-test - pre-test = -306.77 ms, $F_{(1,42)} = 16.324$, $p < 0.05$; $\eta^2 = 0.28$), RV (post-test - pre-test = 0.34 cm/s, $F_{(1,42)} = 14.844$, $p < 0.05$; $\eta^2 = 0.26$) and NJ (post-test - pre-test = -997.0, $F_{(1,42)} = 15.238$, $p < 0.05$; $\eta^2 = 0.27$) and IDE (post-test - pre-test = 2.88°, $F_{(1,42)} = 5.90$, $p < 0.05$; $\eta^2 = 0.02$) but not PL (post-test - pre-test = -0.03 cm, $p > 0.05$; $\eta^2 = 0.03$). When the rotational bias was removed, movement was faster (see Figure 3.4 and 3.5) and smoother (Figure 3.6) but IDE was longer in the untrained hand. Group differences existed for MT (LRL - RLR = 382.604 ms, $F_{(1,42)} = 11.044$, $p < 0.05$; $\eta^2 = 0.21$), PL (LRL - RLR = 0.206 cm, $F_{(1,42)} = 33.04$, $p < 0.05$; $\eta^2 = 0.44$) NJ (LRL - RLR = 832.00, $F_{(1,42)} = 9.835$, $p < 0.05$; $\eta^2 = 0.19$) and IDE (LRL - RLR = 6.42°, $F_{(1,42)} = 15.737$, $p < 0.05$; $\eta^2 = 0.27$). The LRL group recorded a longer MT, PL and greater NJ and IDE compared to the RLR group. There were not group differences on RV (LRL - RLR = -0.18 cm/s, $F_{(1,42)} = 0.918$, $p > 0.05$; $\eta^2 = 0.02$). There were also main effects of Workspace on MT ($F_{(2,42)} = 20.649$, $p < 0.05$; $\eta^2 = 0.50$), RV ($F_{(2,42)} = 11.219$, $p < 0.05$; $\eta^2 = 0.35$) and NJ ($F_{(2,42)} = 18.931$, $p < 0.05$; $\eta^2 = 0.47$) but not PL ($p > 0.05$; $\eta^2 = 0.02$) and IDE ($p > 0.05$; $\eta^2 = 0.02$). Post-hoc tests revealed a significant difference in MT between the group that practiced the task in the contralateral workspace compared to the group that practiced in central workspace (CTL - CEN = 869.61 ms, $p < .05$) and ipsilateral workspaces (CTL - IPS = 655.39 ms, $p < .05$) but there was no difference between the group that practiced in the central and ipsilateral workspace (CEN - IPS = -214.219 ms, $p > .05$). RV was significantly different between the groups that practiced in the contralateral workspace compared to those who practiced in the central (CTL - CEN = -1.10 cm/s, $p < .05$) and ipsilateral workspaces (CTL - IPS = -0.71 cm/s, p

$< .05$) but there was no difference between the group that practiced in the central and ipsilateral workspace (CEN - IPS = 0.39, $p > .05$). RV was lower in the group that performed the task in the contralateral workspace compared to the groups that worked in the central and ipsilateral workspace locations. NJ was also significantly different among the group that practice in the contralateral workspace compared to those that practiced on the central (CTL - CEN = 1896.03, $p < .05$) and ipsilateral workspaces (CTL - IPS = 1493.00 ms, $p < .05$) but there was no significant difference between the group that practiced in the central and ipsilateral workspace (CEN - IPS = -405.02, $p > .05$). A two-way interaction between Group and Workspace on MT ($F_{(2,42)} = 7.301$, $p < 0.05$; $\eta^2 = 0.23$) and NJ ($F_{(2,42)} = 6.216$, $p < 0.05$; $\eta^2 = 0.26$) was observed. MT was significantly different between the LRL group that practiced in the contralateral and those that practiced in the central (CTL - CEN = 1316.25 ms, $p < .05$) and ipsilateral workspaces (CTL - IPS = 1067.81 ms, $p < .05$) but there was no difference between the central and ipsilateral workspace conditions (CEN - IPS = -248.44 ms, $p > .05$). MT was greater in the group that worked in the contralateral compared to the groups that worked in the central and ipsilateral workspaces among the LRL group. There were also no significant workspace differences for MT among the RLR groups i.e. (CEN - IPS = -180 ms, $p > .05$; CTL - IPS = 242.97 ms, $p > .05$; CTL - CEN = 422.97 ms, $p > .05$). NJ was significantly different among the LRL group that practiced in the contralateral workspace compared to individuals who practiced in the central (CTL - CEN = 3046.01, $p < .05$) and ipsilateral workspaces (CTL - IPS = 2476.59, $p < .05$) but there was no difference between the central and ipsilateral workspace conditions (CEN - IPS = -569.42, $p > .05$). Movement among the LRL group was smoother among the groups that worked in the central and ipsilateral workspaces compared to those that worked in the contralateral workspace

location. There were no significant workspace differences in NJ among the RLR group i.e. (CEN - IPS = -240.63, $p > .05$; CTL - IPS = 509.419, $p > .05$; CTL - CEN = 750.04, $p > .05$). Another two-way interaction of Workspace and Test on NJ was observed ($F_{(2,42)} = 4.54$, $p < 0.05$; $\eta^2 = 0.18$). The main effect of Test on NJ was significantly contributed by changes from pre-test to post-test among the groups that practiced in the contralateral workspace (post-test - pre-test = -2071.79, $p < 0.05$), however the groups that practiced in the ipsilateral (post-test - pre-test = -607.95, $p > 0.05$) and central (post-test - pre-test = -311.24, $p > 0.05$) workspaces showed no significant changes from pre-test to post-test. There was a significant two-way interaction between Group and Test on IDE ($F_{(1,42)} = 6.871$, $p < 0.05$; $\eta^2 = 0.14$). IDE was significantly greater from pre-test to post-test for the LRL group (post-test - pre-test = 6.23° , $p < 0.05$) but not the RLR group (post-test - pre-test = -0.23° , $p > 0.05$). Finally there was a three-way interaction between Group, Workspace and Test on IDE ($F_{(2,42)} = 1.043$, $p < 0.05$; $\eta^2 = 0.14$). IDE was greater from pre-test to post-test in the contralateral workspace for the LRL group (post-test - pre-test = 8.91° , $p < 0.05$) and in the ipsilateral workspace for the RLR group (post-test - pre-test = 6.23° , $p < 0.05$, see Figure 3.7). There were no differences in IDE for the LRL group that practiced the task in the central (post-test - pre-test = 4.85° , $p > 0.05$) and ipsilateral workspaces (post-test - pre-test = 4.23° , $p > 0.05$) or the RLR group that practiced in the central (post-test - pre-test = -2.51° , $p > 0.05$) and contralateral workspaces (post-test - pre-test = -4.41° , $p > 0.05$).

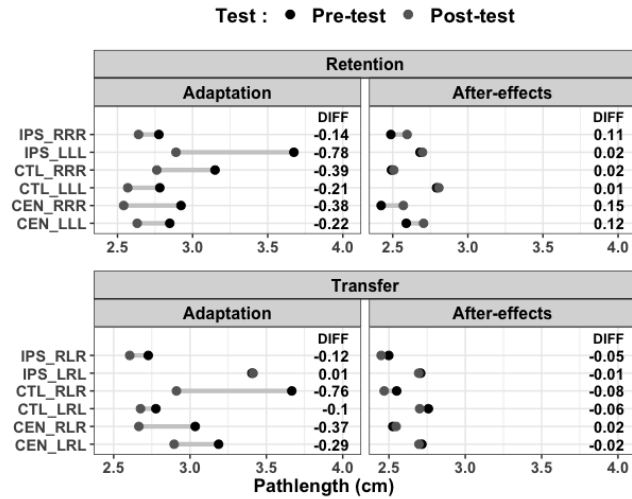


Figure 3.3. Means of median values for Pathlength with standard errors from pre-test to post-test as a function of workspace and group.

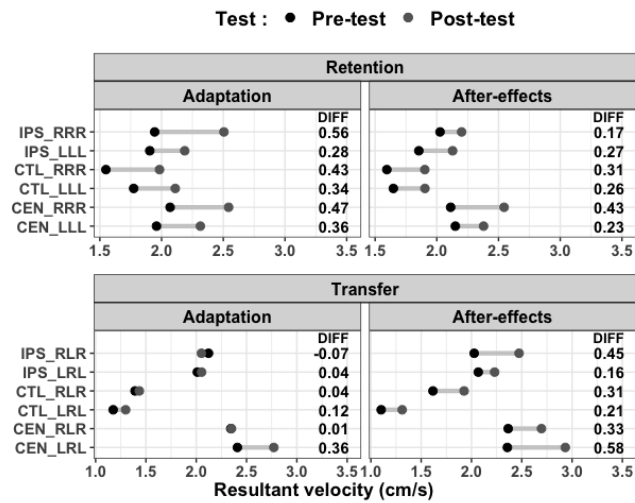


Figure 3.4. Means of median values for movement time with standard errors from pre-test to post-test as a function of workspace and group.

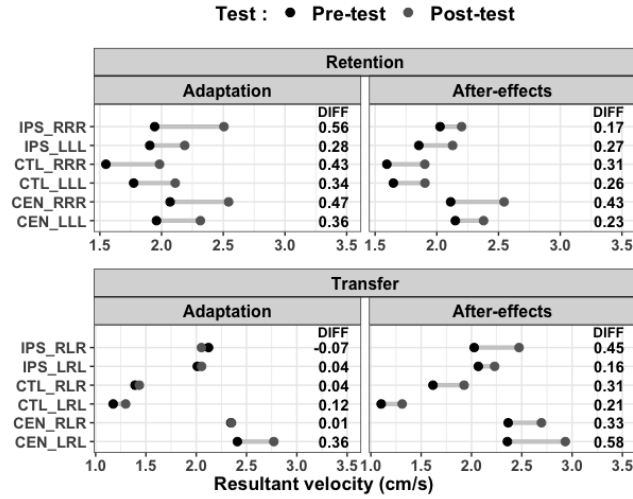


Figure 3.5. Means of median values for resultant velocity with standard errors from pre-test to post-test as a function of workspace and group.

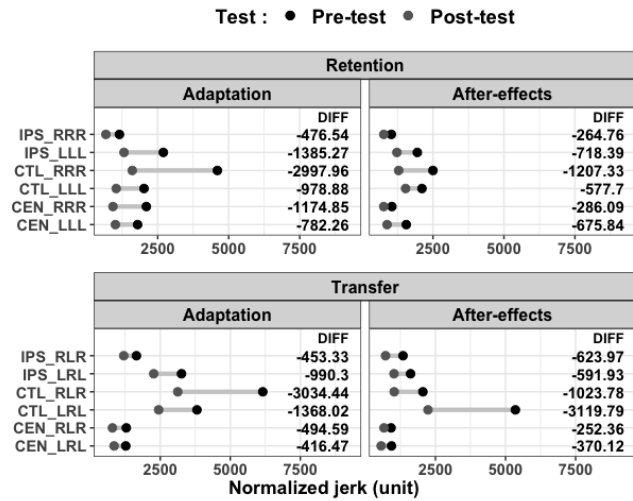


Figure 3.6. Means of median values for normalized jerk with standard errors from pre-test to post-test as a function of workspace and group.

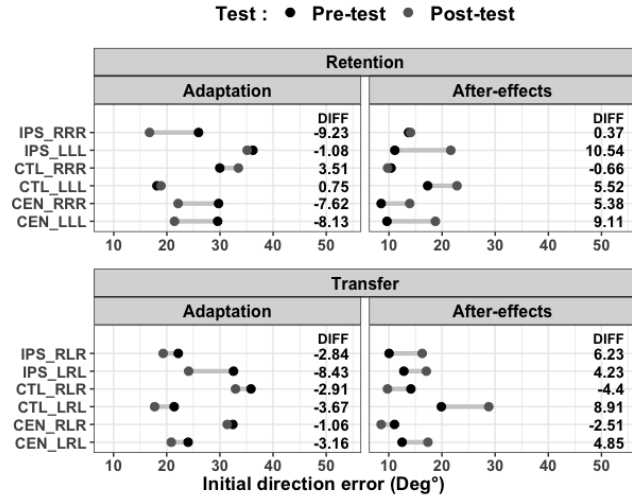


Figure 3.7. Means of median values for initial direction error with standard errors from pre-test to post-test as a function of workspace and group.

Discussion

The dynamic dominance model explains the uniqueness of the two arm controllers responsible for movement control. In this study, we examined workspace location manipulation on bilateral transfer and the consistency of the dynamic workspace in three different workspaces. We started our study by examining retention in experiment 1a to serve as a control and understand how the task is performed in the different workspace locations. Our results indicated significant alterations in movement time, resultant velocity, and normalized jerk across for each group, no matter the workspace location to suggest improvements in the ability of participants to move faster and smoother after training. Our results further showed that workspace and hand differentially affected movement trajectory length. i.e., among the groups that practiced with their left hand (IPS-LLL) in the ipsilateral workspace and the group that practiced with their right hand

in the central (CEN-RRR) and contralateral workspaces (CTL-RRR). The adaptation of pathlength in the central workspace location was consistent with an earlier study by Pan and van Gemmert (2013a), in which performances with the right dominant hand benefited significantly more from training of trajectory length than the left non-dominant hand in the central workspace. After effects were observed for initial direction error and pathlength, while movement got faster and smoother. The group that practiced the task with their left hand showed larger aftereffects for initial direction error and pathlength compared to the group that practiced with their right hand. Movement after the removal of the rotation in the central workspace was smoother than those that practiced in the contralateral workspace indicating the contralateral workspace may have posed a greater amount of difficulty.

In the second experiment, we observed bilateral transfer of pathlength only occurred for the group that trained with the left hand and tested on the right hand, i.e., RLR. Post-hoc results movement in the contralateral workspace was significantly slower and less smooth than those in the central and ipsilateral workspaces, which shows the contralateral workspace poses a greater difficulty than the other two workspaces. The interactions effects of workspace and Test on movement time and normalized jerk indicated bilateral transfer occurred only in the contralateral workspace (this workspace requires participants to move across the midline). Significant after-effects of initial direction error was observed for the LRL group in the contralateral workspace and for the RLR group in the ipsilateral workspace. After-effects indicated a significant improvement in movement time and resultant velocity. Normalized jerk only improved significantly in the contralateral workspace. Overall, the RLR group was faster, recorded a shorter trajectory length, and had smoother movements than the LRL. Post-hoc tests revealed

movement was slower and less smooth in the contralateral workspace was significantly greater than that of the central and ipsilateral workspaces further confirming the challenge posed by the contralateral workspace. Movement time was also slower and less smooth among the LRL group that practiced the task in the contralateral workspace compared to the central and ipsilateral workspaces. Participants in the contralateral workspace recorded a lower resultant velocity than those in the central and ipsilateral workspaces. Velay, Daffaure, Raphael, & Benoit-Dubrocard, (2001) showed a similar ipsilateral advantage of goal-directed tasks over contralateral workspace where they attributed to a longer processing time required to receive information about the task from the opposite hemisphere. Since there were no significant aftereffects of pathlength, the observed transfer may be effector dependent due to practice rather than the creation of an internal model based on pathlength.

Past researchers who studied visuomotor adaptation have provided conflicting results on the generalization of visuomotor adaptation across different workspaces (Heuer & Hegele, 2011; Krakauer et al., 2000; Thomas & Bock, 2012; Vetter et al., 1999; Woolley et al., 2007). The use of different variables and protocols used may explain some differences across studies. The protocol differences for potential contrasts in previous works include, prior knowledge (Miall, 2002), arm used (Bock, 2005; Prablanc & Jeannerod, 1975; Thomas & Bock, 2012), the direction of movement (Pearson et al., 2010), arm posture at the start of movement (Gandolfo et al., 1996; Ghahramani & Wolpert, 1997), the position of the target (Woolley et al., 2007), or the order of target presentation (Welch et al., 1993). We also reasoned that workspace could modulate many of these protocol differences known to influence the transfer of visuomotor adaptation tasks. Thus, even with differences among study outcomes, our general hypothesis was that workspace

does influence adaptation to a visuomotor rotation as well as bilateral transfer. We predicted an asymmetric transfer of movement parameters in the central workspace, whereas, in the ipsilateral and contralateral workspaces, a symmetric transfer pattern would be observed. Findings revealed a parametric-dependent transfer across workspaces.

Our results showed an asymmetric transfer of pathlength so that reduction of pathlength only existed for the right hand following the left-hand training across workspaces to support our first hypothesis. An incomplete establishment of an initial internal model prior to the exposure to the rotation would explain why participants produced no aftereffects for pathlength. There was no adaptation of movement time, initial direction accuracy, resultant velocity, and normalized jerk in the central and ipsilateral workspaces. This is similar to others (Wang 2008; Lei et al., 2013), where no bilateral transfer existed for resultant velocity and initial direction accuracy for the right and left hands. However, these observations contradict results of previous studies (Sainburg and Wang, 2002; Wang and Sainburg, 2006) which involved a similar workspace for visual feedback and movement performance. One explanation for bilateral transfer is access to information regarding different aspects of movement parameters for each arm controller per the tenets of the dynamic dominance model (Sainburg & Wang, 2002). According to Wang (2008), the performance of the visuomotor task with both hands provides the movement system with different possible solutions, which leave the executive system to select the most optimum solution. The motor system selects a solution based on the compatibility requirements of the task and proficiency of the arm controller. With this line of reasoning, when performing a task with the right hand following the training of the left hand, the motor system may favor the use of the right hand as an optimum solution over the other due to the inhibition of information by the arm

controller. The lack of transfer in the central workspace could be explained by the competing flow of information and search for an optimal solution between the two arm controllers, leading to an incomplete processing of the task's neural representation. In the ipsilateral workspace, Lei et al. (2013) argued that a lack of adaptation could the inability of the hemisphere responsible for movement control determine the arm dominance in the workspace. Following this line of reasoning, directional information based on vision often accessed by the dominant arm could be inhibited for both arms leading to a lack of transfer. The present study trained the left arm, which may have left some task-specific information for the hemisphere controlling the right hand. The left arm's inability to benefit from training the right hand on pathlength can be attributed the arm dominance. The motor output of the non-dominant arm is often noisy (Annett, Annett, Hudson, & Turner 1979), which can affect task performance and explain a lack of transfer to the left hand. Furthermore, we speculate that since the left hand (i.e., non-dominant hand) is not the preferred hand for everyday motor task performance hence may not have an existing internal model for the task performance, making it easier for creating a new internal model rather than switching from an existing one (Wada et al., 2003) for pathlength estimate. This could possibly make trajectory information available for the right hand with limited access for the left hand explaining an asymmetric transfer of pathlength across workspaces. Despite an asymmetric pattern of bilateral transfer of pathlength in the contralateral workspace, our findings seem not to back the dynamic dominance model due to the symmetric transfer of movement time and normalized jerk, partly supporting the third hypothesis. As shown in the results, the contralateral workspace seemed to pose a greater challenge (i.e., longer movement time, requiring more processing time and more jerky movements) than the two other workspace locations. While ipsilateral rather than

contralateral reaches are more preferred in everyday activities (Gabbard & Rabb, 2000; Stins, Kadar, & Costall, 2001; van Kordelaar, van Wegen, & Kwakkel, 2012), possibly due to the biomechanical efficiency of ipsilateral reaches (Gabbard & Rabb, 2000) understanding the perceptual-motor system during task performance in the contralateral has important implications. For instance, visuomotor adaptation using the prism paradigm has been used to train individuals with spatial neglect (P. Chen, Pitteri, Gillen, & Ayyala, 2018; Rossetti et al., 1998; Saj, Cojan, Assal, & Vuilleumier, 2019; Yang, Zhou, Chung, Li-Tsang, & Fong, 2013). Extending our understanding of adaptation to a workspace that requires crossing the body's midline could improve rehabilitation strategies for treating spatial neglect.

Another practical application of visuomotor adaptation is the use of visual displays for remote guidance in telemedicine (Ballantyne, 2002), telepresence for remote guidance of robotics for rescue missions (Klamt et al., 2020), and space missions (Fairchild et al., 2016). Some of the tasks require individuals to move across the midline for task execution. The primary sources of adaptation errors stem from calibration problems or camera offsets of the visual feedback on the head-mounted virtual reality displays, which may pose visual displacements problems and requires adaptation to the new situations -systematic errors (Lee & Park, 2020).

Limitations

Our study also explored different movement parameters that could bolster our understanding of visuomotor adaptation mechanisms and changes the motor system undergoes since visuomotor tasks often consist of both temporal and spatial features (see Elangovan et al.,

2017). To understand the full picture, neurophysiological evidence is needed to understand how the workspace modulates brain activities during adaptation.

Conclusion

The study set out to assess the consistency of the dynamic dominance model in three different workspace setups. The current study showed bilateral transfer across the different workspace locations might be parameter-dependent. We observed a pattern of transfer for directional information such as pathlength to be asymmetric across limbs in all workspace locations and a symmetric pattern of transfer of movement time and normalized jerk unique to the contralateral workspace. Different parameters were transferred based on the limb used for training and the workspace location the task was being performed. Emphasis should be placed on different movement features to help better understand the mechanisms of interlimb transfer and workspace manipulation.

CHAPTER 4. NEURAL CORRELATES OF VISUOMOTOR ADAPTATION – WORKSPACE EFFECTS

Introduction

The accuracy of goal-directed movements depends on the quality of motor plans formed and updated during motor learning (Perfetti et al., 2011). Motor plans are retrieved as memories formed during learning through feedback (i.e., actual sensory consequences of executed movement) and feedforward (i.e., predicted movement outcome) mechanisms (Perfetti et al., 2011). Motor plans are not sufficient for accurate movements when learning to adapt to a visual perturbation and must be updated during movement execution via a feedback mechanism. Adequate practice leads to the integration of error information about the movement trajectory into the motor plans through a feedforward process (Perfetti et al., 2011) which is retrieved as learned movement patterns. Adaptation ensues by learning the proper feedforward motor commands (Grafton, Schmitt, Van Horn, & Diedrichsen, 2008). The sensorimotor system updates sensory and motor information (Wolpert & Flanagan, 2001) sampled from the workspace environment (Cisek & Kalaska, 2010) during visuomotor adaptation. Successful performance of visually guided movements requires an estimate of the target's spatial location in the extrinsic workspace (Brayanov, Press, & Smith, 2012; Kawato, 1996). Unsurprisingly, making workspace configuration crucial to visuomotor adaptation (Heuer & Hegele, 2011; Krakauer et al., 2000; Liew et al., 2018; Thomas & Bock, 2012; Vetter et al., 1999; Woolley et al., 2007).

While some researchers have shown adaptation to be specific to a particular workspace (Thomas & Bock, 2012; Woolley et al., 2007), evidence to the contrary exists to indicate that adaptation can generalize to other workspaces (Heuer & Hegele, 2011; Krakauer et al., 2000; Lei,

Johnson, & Wang, 2013; Vetter et al., 1999). Both Woolley et al. 2007 and Thomas & Bock, (2012) showed individuals could adapt to different rotations when the targets were presented in a specific workspace location. Contrary to that, Lei et al. (2013) demonstrated visuomotor task could generalized from medial to a lateral workspace and vice versa; however, the generalization tended to reduce when the visual and motor workspaces were separated (when the task space and the visual feedback (i.e., screen location) were in different physical locations). Heuer & Hegele, (2011) also reported visuomotor adaptation benefits in a workspace that required midline crossing after practicing in the lateral workspace. There are different representations of workspace in different studies, i.e., location of horizontal tablet on which participants make aiming movements with a finger (Heuer & Hegele, 2011) or stylus (Pan & Van Gemmert, 2013), force traducers with corresponding visual feedback of force applied (i.e., visual workspace) (Woolley, Tresilian, Carson, & Riek, 2007), and a virtual visual display of computer-generated targets (Thomas & Bock, 2012). Understanding workspace effects on adaptation to a visually rotated target can present insight into understanding control of visuomotor adaptations.

There are two primary assessments of learning which involve observing movement outcomes during and after task performance and real-time psychophysiological measures (Kiefer, Gualberto Cremades, & Myer, 2014). Some movement outcomes for visuomotor adaptation task paradigms include the duration for task completion (Heuer & Hegele, 2011; Pan & van Gemmert, 2013a), directional errors (Heuer & Hegele, 2011; Krakauer et al., 2000; Lackner & Dizio, 1994; Thomas & Bock, 2012) and movement trajectory length (Heuer & Hegele, 2011; Pan & van Gemmert, 2013a) that provide a measure of movement quality. In contrast, psychophysiological measures include the use of neuroimaging techniques to assess changes in neural responses to

adaptation (Etnier, Whitwer, Landers, Petruzzello, & Salazar, 1996; Kirby, Pillai, Carmichael, & Van Gemmert, 2019; Seidler, Noll, & Chintalapati, 2006; Smith, McEvoy, & Gevins, 1999).

Researchers have tried to understand the neuronal basis of behavioral changes during motor skills acquisition using neuroimaging techniques such as functional magnetic resonance imaging (fMRI) (Kirby et al., 2019; Seidler et al., 2006) and electroencephalograms (EEGs) (Hatfield, Haufler, Hung, & Spalding, 2004; Hillman, Apparies, Janelle, & Hatfield, 2000).

Neuronal changes such as frequency oscillations occurring in the brain can provide insight into how motor skills are processed by individuals (Lin, Shaw, Young, Lin, & Jung, 2012; Min & Park, 2010). Changes in brain activity in the posterior parietal, premotor, and frontal regions occur in response to visuomotor adaptation to visually rotated targets (Anguera, Seidler, & Gehring, 2009; Gentili, Bradberry, Oh, Hatfield, & Contreras-Vidal, 2011; Ghilardi et al., 2000; Huber, Ghilardi, Massimini, & Tononi, 2004; Inoue et al., 2000), suggesting the involvement of these brain structures in motor-circuits involved in motor adaptation. In addition, changes in neural activities represent plasticity due to learning and adaptation (Gentili et al., 2011; Huber et al., 2004). While not all plasticity indicates learning, plasticity precedes learning; hence, different cortical plasticity dynamics may offer insights into learning variations across individuals (Espenhahn et al., 2019). It is widely accepted that different oscillatory bands have their corresponding behavioral correlates (Classen, Gerloff, Honda, & Hallett, 1998; Seeber, Scherer, & Muller-Putz, 2016). For instance, a decrease in beta-band oscillations (13-30Hz) or movement-related beta desynchronization in the sensorimotor regions indicates increased movement-related activities (Pfurtscheller & Lopes da Silva, 1999; Pfurtscheller, Zalaudek, & Neuper, 1998; Salmelin & Hari, 1994; Stancak & Pfurtscheller, 1995), and subcomponents of beta activity (i.e.,

post-movement beta rebound) predicts motor learning ability after stroke (Espenhahn et al. 2020). Theta activities in the frontal regions also reflect cognitive control (Zamorano et al., 2020) and top-down processes (i.e., voluntary component) of spatial attention (Hopfinger, Buonocore, & Mangun, 2000). Voluntarily attending to the visual target improves target localization and performance (Bashinski & Bacharach, 1980; Posner, 1980; Tong, 2003).

Current neuroimaging and brain stimulation studies on visuomotor adaptation show that adaptation relies primarily on a cortico-cerebello-thalamo-cortical loop involving the sensorimotor cerebral regions and subcortical structure involved in motor control (Doyon, Penhune, & Ungerleider, 2003; Kirby et al., 2019; Savoie, Thenault, Whittingstall, & Bernier, 2018; Tzvi, Loens, & Donchin, 2021; Weightman, Brittain, Punt, Miall, & Jenkinson, 2020). Savoie et al., (2018) determined an increase in theta activity in the mid-frontal and right parietal regions was associated with processing visuomotor prediction errors, one of the sources of errors during adaptation (a mismatch between predicted and sensory outcome of movement). Kirby et al, (2019) revealed in an fMRI study, the motor planning regions e.g., left precuneus was sensitive to visuomotor adaptation when practicing with the dominant arm. Both studies (Savoie et al., 2018; Kirby et al., 2019) were performed only in a central workspace (i.e., participant's midline). With behavioral evidence for visuomotor adaptation differences across workspaces (Heuer & Hegele, 2011; Lei et al., 2013; Thomas & Bock, 2012; Woolley et al., 2007), less is known about neural activity changes when manipulating the workspace. Thus, we chose to investigate how workspace manipulation modulates behavioral and neurophysiological changes during visuomotor adaptation to better understand its control on both a neural and a behavioral

level. More specifically, in this study we modified the workspace by letting participants reach visually rotated targets in three different start locations represented as the position of tablet.

More specifically, evidence exists for adaptation patterns in the central and ipsilateral workspace locations. However, there is insufficient data to support the generalization of adaptation across various workspace locations, such as the contralateral workspace. Therefore, this study aims to provide insight into the generalization of adaptation across workspace locations using a comprehensive list of movement parameters beyond the most popular measures - initial direction and endpoint errors – and ensuing neurophysiological correlates. Of the neurophysiological measures employed in previous visuomotor adaptation studies, EEG has proved to provide insights in visuo-motor adaptation processes (Gentili et al., 2015; Savoie et al., 2018). Neural activities such as alpha suppressions in the right somatosensory cortex are observed during movement selection in a mental stimulation task (Brinkman, Stolk, Dijkerman, de Lange, & Toni, 2014), whereas a decrease in beta activity in the sensorimotor regions is related to movement-related activities (Pfurtscheller & Lopes da Silva, 1999; Pfurtscheller, Pichler-Zalaudek, Ortmayr, Diez, & Reisecker, 1998; Salmelin & Hari, 1994; Stancak & Pfurtscheller, 1995). In the current study, we explored how changes in neural activities are affected by workspace manipulation during a visuo-motor adaptation task. We hypothesize that participants will concurrently adapt to a visuomotor rotation in three different workspace locations without interference and adaptation will be associated with specific changes in brain oscillatory behaviors within the frontal, sensorimotor, and parietal areas of the brain when manipulating various workspaces. Specifically, a contralateral workspace location will be associated with higher cortical processing compared to the central and ipsilateral workspace

locations, consistent with the behavioral variables. We expect that this higher cortical processing will be reflected in oscillatory activity specifically in sensory-motor areas of the brain.

Methods

Participants: Twenty-four university students (age, 20.04 ± 1.68 yrs, mean \pm S.D., all right-handed; 12 Females) with normal or corrected-to-normal vision took part in the study. All participants were right-hand dominant according to the Edinburgh Handedness Inventory (Oldfield, 1971) and had a laterality quotient of 0.6 or higher. The purpose of the study was communicated to all participants before having them sign a consent form prior to the study. The study protocol was approved by the Institutional Review Board for Human Subjects Research at Louisiana State University.

Equipment: A WACOM (Intuos3 12 x19) digitizer tablet connected to a PC with a (50x30cm) monitor was used for collecting pen recordings and provide visual feedback of pen movements. A normal looking electronic non-inking pen (WACOM ZP-130) was used to make drawings on the tablet. The sampling rate of the X- and Y- position of pen tip was 200Hz and spatial resolution was 0.0005 cm in X- and Y- direction. A 32-channel EEG system (BrainProducts, Gilching, Germany) equipped with 32 Ag/AgCl electrodes attached to caps that were adapted to individual head sizes was used to register neural activity for all conditions. A conductive gel (EASYCAP GmbH, Germany) was filled between the electrode and the scalp to increase contact and reduce impedance to a value below 10 kOhm. EEG data was recorded at electrode sites Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, FT9, TP10, TP9, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, O1, Oz, and O2 at a sampling rate of 500 Hz and a 60Hz notch filter. One electrode (vEOG) placed below the right eye were used to capture vertical

electrooculogram (EOG) to detect eye movements. AFz and FCz served as the ground and reference electrodes, respectively (see Figure 4.1).

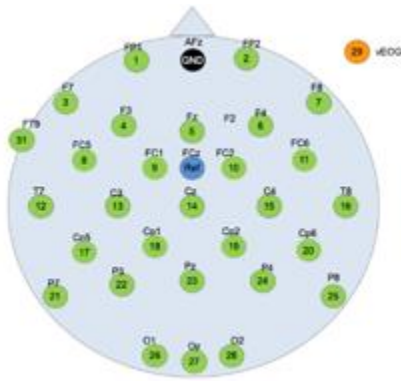


Figure. 4.1. Electrode placement.

Adaptation Task

The setup included a horizontal digitizer tablet connected to a vertical monitor for visual feedback. The monitor was situated in front of the participants; however, the position of the horizontal tablet was moved depending on the condition. Participants sat in front of a monitor and a digitizer tablet. They were instructed to move the digital pen over the tablet. The pen movements were shown in real-time on the monitor in front of the participants. Participants were asked to draw a line from a start position (a black circle in the center of the monitor; 0.5 cm diameter) to one of 4 target positions (a black circle 2.5 cm away from the start position; 0.5 cm diameter) without lifting the pen from the start position.

After the start circle appeared, the participants were instructed to move the pen tip within the start circle. When the pen tip entered the start circle, the start circle disappeared while the target circle appeared. Participants needed to move as fast and as accurately as possible the pen to

the target. Targets were located either 2.5cm above, below, to the right, or to the left of the start position. Each trial was composed of a series of each of the four target positions, and thus four discrete aiming movements were made during a trial. The online visual feedback of the movement trajectory was rotated 45° clockwise.

Experimental Procedure

On arrival at the test location, participants were given a copy of an informed consent to read and sign, to fill a handedness questionnaire and a short demographic questionnaire. After that, we prepared the EEG electrodes, which lasted about 15 min. The participant was asked to sit comfortably in a chair with a screen for visual feedback and an opaque digitizer tablet (record movements made with a pen). They were asked to keep minimal body movements for EEG resting measures. Impedances of the recorded channels were kept below 10 kOhm. These resting measures consisted of a 1-minute recording with their eyes open and another 1 minute with eyes closed. The eyes-open measure was to serve as the baseline to which the visuomotor task will be compared. Afterwards, they were asked to prepare for the first session of the task. During the preparation phase, no EEG registrations were performed.

For the visuomotor task, participants were asked to use the pen/stylus to make drawing movements on the tablet while they received visual feedback on the screen. Participants were asked to move the tip of the pen to the center of a black central circle and hold it in this circle till it disappears. When the central circle disappears a new circle, called target, appears either to the left, right, above, or below the location of the black central circle that just disappeared. Participants were required to make drawing movement as fast and as accurate as possible to the new target. The location of the targets was unpredictable. The time and accuracy of the drawing

movement between the central black circle and the new targets were measured. Thus, the trial starts after the participant enters the black central circle and ends when they stopped in the target and subsequently lift the pen. EEG was constantly registered across trials. At the end of the task, additional resting EEG measurements with eyes open and closed for 1 min were performed. Workspace location (indicating position of the digitizer tablet relative to the participant) was manipulated, 3 of them in total, a workspace between the two shoulders (Central), the second, participants will train the task with the workspace outside the shoulder of the hand holding the stylus (ipsilateral). In contrast, the third workspace location required training the task with the workspace outside the shoulder opposite to the hand holding the stylus (contralateral). EEG was measured for all workspace conditions. Each participant worked in all three workspaces with the dominant hand (see Figure 4.2). In total, participants were randomly assigned one of six runs (i.e., representing order of workspace manipulation) for the whole experimental design (CEN-IPS-CTL, CEN-CTL-IPS, IPS-CEN-CTL, IPS-CTL-CEN, CTL-CEN-IPS, and CTL-IPS-CEN).

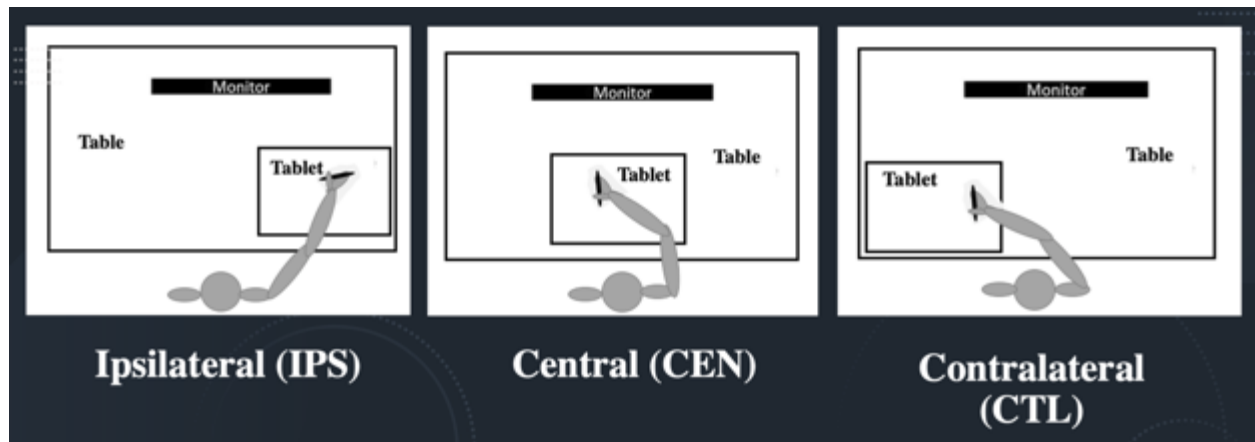


Figure 4.2. Experimental set up.

Participants view the cursor motion on a vertically oriented monitor, which moves according to stylus movement on a horizontal tablet. Participants were randomly assigned to one of three workspace locations (indicating the start position and location of the tablet). Note, the center of the workspace, thus the start position is either located ipsilateral to the upper limb (left panel), central to the body midline (middle panel), or contralateral to the upper limb (right panel).

Table 4.1. Experimental trial progression

	IPS			CEN			CTL		
Trial blocks	Block 1	Block 2-9	Block 10	Block 1	Block 2-9	Block 10	Block 1	Block 2-9	Block 10
Number of trials	4	32	4	4	32	4	4	32	4

Behavioral data

The pen tip data recordings were processed with a custom program developed in MATLAB (MathWorks Inc., Natick, MA, USA) (e.g., Pan & van Gemmert, 2013). The position signals were filtered using a Butterworth 4th order dual pass filter with a cut-off frequency of 16 Hz. The movement segments were parsed using the 5% of the peak velocity criterion in the velocity profile to determine movement onset (i.e., start) and offset (i.e., end). For each workspace, there are 10 trial blocks consisting of 4 trials (See Table 4.1).

Dependent Variables

The following dependent variables were estimated for the first and tenth trial blocks:

- Initial direction error-IDE (degrees): the angle between the vector from the center of the home circle position and the center of target position and the vector between the onset location of the movement and the location at 80 ms into movement.
- Movement time-MT (s): The stroke duration between the onset and offset of the movement.
- Pathlength-PL (cm): Cumulative length of the movement trajectory between onset and offset of the movement.
- Normalized jerk-NJ (unitless): The rate of change of acceleration normalized for stroke size and duration (cf. Van Gemmert, Teulings, & Stelmach, 1998).
- Resultant velocity-RV (cm/s): Square root of the sum of the squared velocity in the x- and y-direction between onset and offset of the movement.

EEG data preprocessing

Offline EEG data were preprocessed using the Brain Vision Analyzer 2.0 (Brain Products, Gilching, Germany) by applying a 0.5 Hz high-pass and a 70 Hz low-pass filter. Vertical eye movements were corrected using independent component analysis (ICA), and epochs containing further artifacts were visually identified and manually rejected using a semi-automatic raw data inspection tool. Artefact free segments were then included for further processing.

To evaluate sustained changes in brain oscillatory activity over time, seven different conditions consisting of eyes closed, eyes open before and after the main tasks, and (3) visuomotor adaptation tasks were used. To do so, first each condition was segmented in one second segments (e.g., having a max of 60 segments for eyes open condition). Then, a fast Fourier transformation (FFT) with a 10% sliding hannin window was subsequently computed on each segment. Frequency spectra of the artefact-free segments were averaged either for each block (in the adaptation conditions) or for resting conditions (eyes open and closed) and the mean activity (μV) in the theta range (4-7 Hz), alpha range (8–12 Hz), and beta range (18–30 Hz) was calculated and exported. All frequency spectra differences from baseline measure with eyes open condition were calculated, i.e., the frequency bands for each condition were subtracted from the pre-eyes open condition, which indicates the task-specific changes in oscillatory activity. Electrodes of interest were selected via visual inspection of the brain topographic plots and graphs showing workspace effects in the region of interests (i.e., sensorimotor regions). Major changes in the alpha and beta band activity were only visually detected within the right hemisphere and at central and parietal regions

Statistical analysis: All data were checked for normal distribution and sphericity, using a Shapiro-Wilk's test and Mauchly's test, respectively. In the case of non-sphericity, the Greenhouse-Geiser correction was applied. Since the data were skewed, the median value was computed and used for the ANOVAs. A repeated-measures ANOVA with workspace location and trial blocks (1 and 10) as within factors was performed for five behavioral variables. A repeated-measures ANOVA with workspace location (CEN, IPS, CTL) as within factor was performed for some select electrodes over central and parietal regions (C4, CP2, CP6, P4 and P8) measuring brain oscillation (i.e., alpha, and beta waves) over the duration of the task and task-relevant brain areas. Statistical significance was set at the standard p-value of 0.05 using the R software. Significant results were followed by Post-hoc tests (i.e., Bonferroni correction).

Results

Behavioral variables

Initial direction error: Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated for both workspace ($\chi^2(2) = .11, p > .05$) and the interaction effects between workspace and trial blocks ($\chi^2(2) = 0.56, p > .05$). There was a significant main effect of trial blocks (block 10 - block 1 = -4.53° , $F_{(1, 23)} = 5.06, p < .05$; $\eta^2 = 0.18$) but not workspace ($F_{(2, 46)} = 1.635, p > .05$; $\eta^2 = 0.07$) on IDE. There was a significant decrease of IDE from the first block to the last block of trials across workspace locations. There was also no significant interaction effect between workspace and trial blocks ($F_{(2, 46)} = .607, p > .05$; $\eta^2 = 0.03$). There was a significant reduction in IDE in all three workspaces.

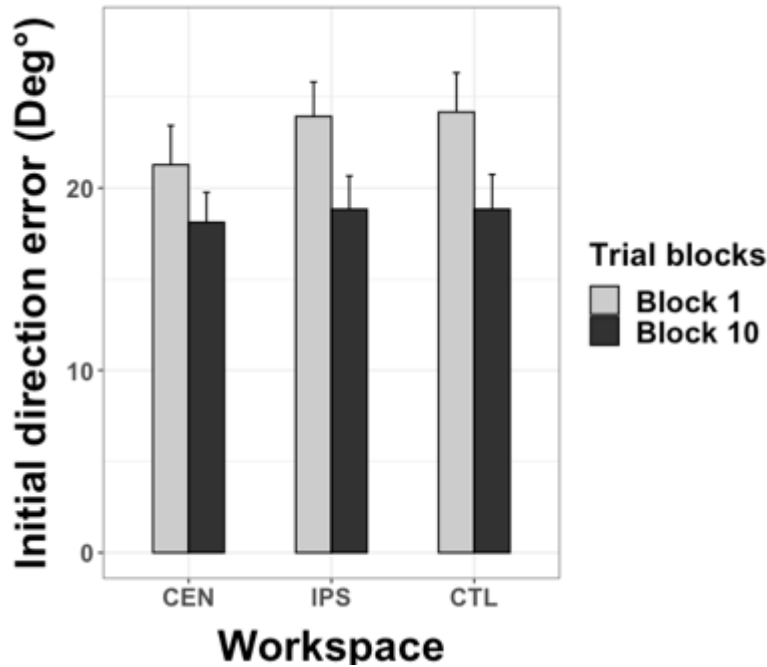


Figure 4.3. Trial blocks for median scores of initial direction error as a function of workspace and group.

Pathlength: Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated for both workspace ($\chi^2(2) = 1.85, p > .05$) but was violated for interaction effects between workspace and trial blocks ($\chi^2(2) = 7.73, p < .05$) hence a Greenhouse-Geisser correction was used. There was a significant main effect of Workspace ($F_{(2, 46)} = 28.96, p < .05; \eta^2 = 0.56$) and trial blocks (block 10 - block 1 = - 0.32 cm, $F_{(1, 23)} = 24.21, p < .05; \eta^2 = 0.51$) but no significant interaction between the two ($F_{(1.54, 35.48)} = 3.08, p > .05; \eta^2 = 0.12$) were observed on PL. There was a significant decrease of PL from the first block to the last block of trials across workspace locations. Pairwise comparisons indicated significant differences between all three workspaces i.e., central and ipsilateral workspace (CEN – IPS = 0.26 cm, $P < 0.05$), contralateral

and ipsilateral (CTL – IPS = 0.50cm, $P < 0.05$), and contralateral and central workspaces (CTL – CEN = 0.25 cm, $P < 0.05$). PL was significantly longer in the contralateral compared to both the ipsilateral and central workspace location. PL in the central workspace was longer than in the ipsilateral workspace location. Nonetheless, there was a significant reduction in PL from the first to the last trial block across all three workspace locations.

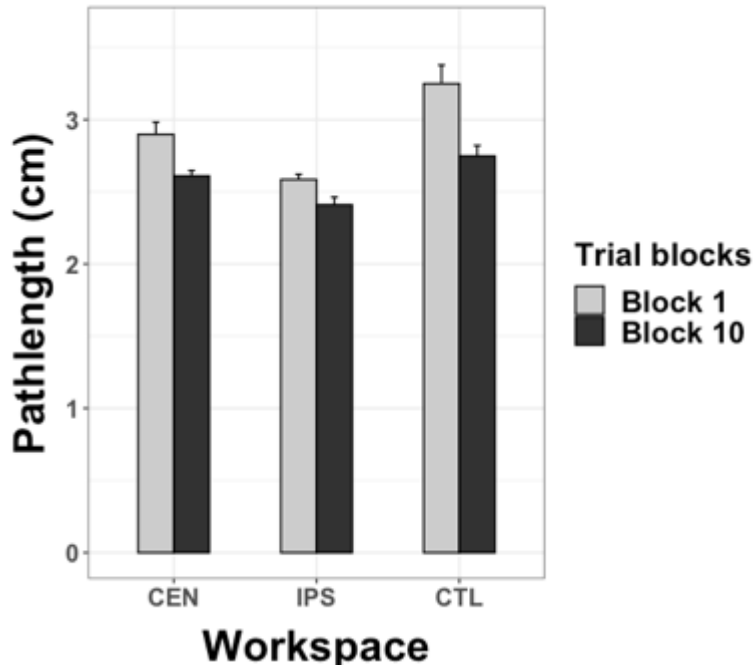


Figure 4.4. Trial blocks for median scores of pathlength as a function of workspace and group.

Movement time: Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated for both workspace ($\chi^2(2) = 3.36$, $p > .05$) and the interaction between workspace and trial blocks ($\chi^2(2) = 0.83$, $p > .05$). There were significant main effects of Workspace ($F_{(2, 46)} = 7.19$, $p < .05$; $\eta^2 = 0.24$) and trial blocks (block 10 - block 1 = -207.75 ms, $F_{(1, 23)} = 44.54$, $p < .05$; $\eta^2 = 0.66$) but no significant interaction effects between workspace and trial blocks ($F_{(1.259, 28.956)} = .07$, $p > .05$; $\eta^2 = 0.003$) were found for MT. MT was significantly

lower for the last trial block. Pairwise comparisons indicated significant differences between the contralateral and ipsilateral workspaces (CTL – IPS = 316.56 ms, $P < 0.05$) but not between the central and ipsilateral workspace (CEN – IPS = 193.91 ms, $P > 0.05$) or the contralateral and central workspaces (CTL – CEN = 122.66 ms, $P < 0.05$). MT was lower in the ipsilateral compared to the contralateral workspace location however MT reduced significantly from the first to the last block of trials in all three workspaces.

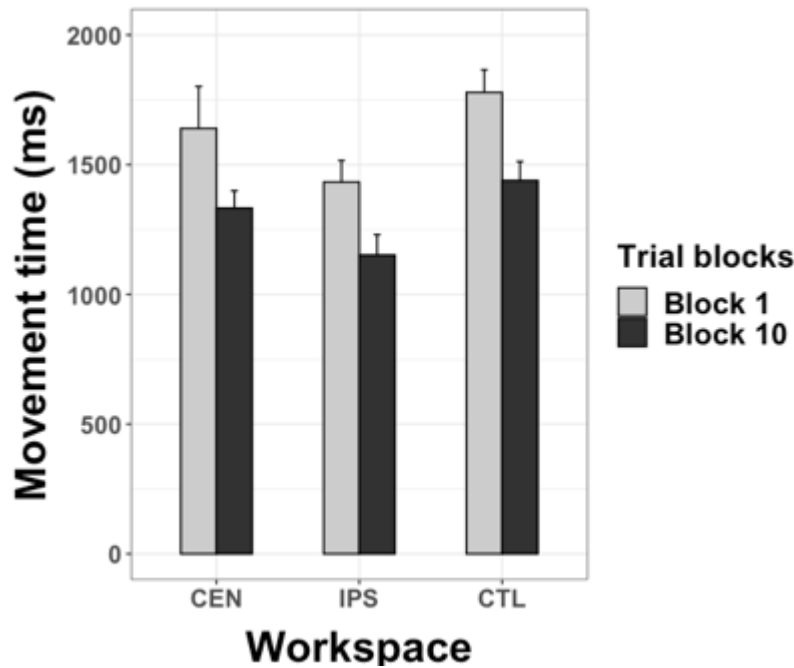


Figure 4.5. Trial blocks for median scores of movement time as a function of workspace and group.

Resultant velocity: Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated for both workspace ($\chi^2(2) = 3.98$, $p > .05$) and interaction effects of Workspace and trial blocks ($\chi^2(2) = 0.46$, $p > .05$). There were no significant main effect of Workspace ($F_{(2, 46)} = 1.84$, $p > .05$; $\eta^2 = 0.07$) as well as interaction effects of Workspace and trial

blocks ($F_{(2, 46)} = 2.73$, $p > .05$; $\eta^2 = 0.11$), however there was a significant effect of trial blocks (block 10 - block 1 = 0.25 cm/s, $F_{(1, 23)} = 19.84$, $p < .05$; $\eta^2 = 0.46$) on RV. RV was significantly higher from the first to the last trial block across workspace locations.

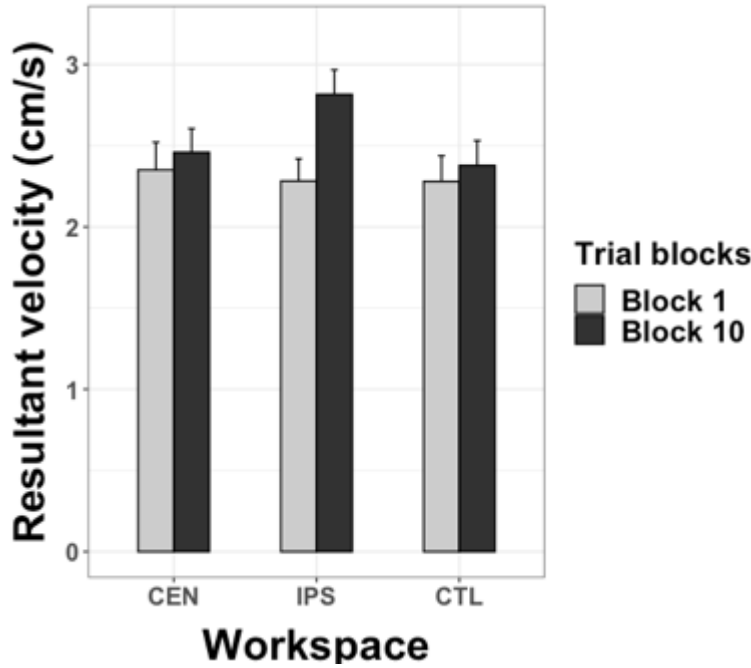


Figure 4.6. Trial blocks for median scores of resultant velocity as a function of workspace and group.

Normalized Jerk: Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated for workspace ($\chi^2(2) = 8.44$, $p < .05$) and interaction between workspace and trial blocks ($\chi^2(2) = 9.57$, $p < .05$) hence a Greenhouse-Geisser correction was used. There was no significant effect of Workspace ($F_{(1.52, 34.89)} = 2.29$, $p > .05$; $\eta^2 = 0.09$), and an interaction effect between both workspace and trial blocks ($F_{(1.48, 34.00)} = 0.17$, $p > .05$; $\eta^2 = 0.01$) on NJ. However

there was a significant effect of trial blocks (block 10 - block 1 = -556.01, $F_{(1, 23)} = 1.718$, $p < .05$; $\eta^2 = 0.35$). NJ was significantly lower from the first to the last trial block across workspace locations.

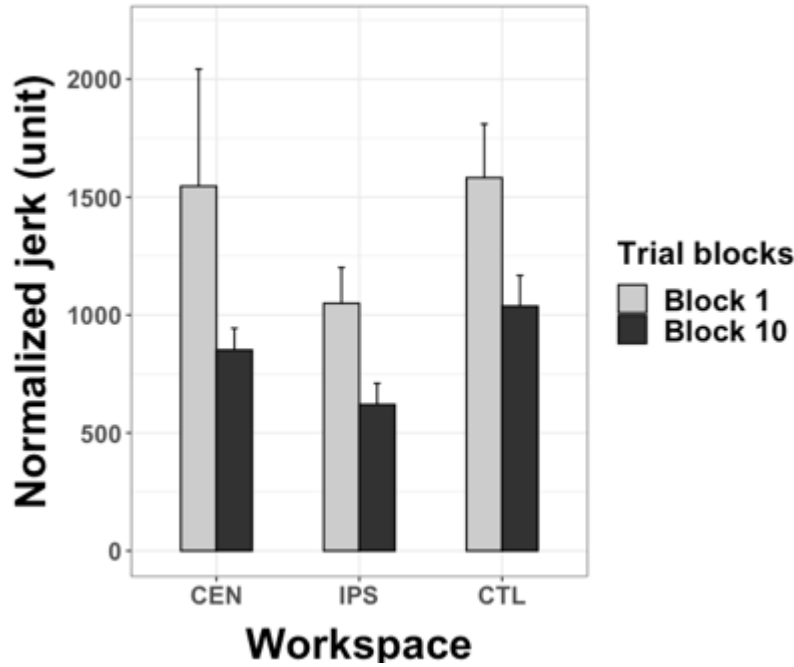


Figure 4.7. Trial blocks for median scores of normalized jerk as a function of workspace and group.

Neurophysiological variables

Mauchly's Test of Sphericity indicated that the assumption of sphericity has not been violated for workspace-related changes in alpha on electrodes C4 ($\chi^2(2) = 2.962$, $p > .05$), CP2 ($\chi^2(2) = 2.819$, $p > .05$), P4. ($\chi^2(2) = 2.336$, $p > .05$), P8 ($\chi^2(2) = 2.660$, $p > .05$) and CP6 ($\chi^2(2) = 2.288$, $p > .05$). There was a significant main effect of Workspace on electrode C4 ($F_{(2, 46)} = 10.04$, $p < .05$; $\eta^2 = 0.30$). Pairwise comparisons indicated there was a significant increase in

alpha activity in the contralateral workspace compared to the central (CTL- IPS = 0.05 μV , $p < .05$), and ipsilateral workspaces (CTL- IPS = 0.09 μV , $p < .05$).

There was a significant main effect of Workspace on electrode CP2 ($F_{(2, 46)} = 3.82$, $p < 0.05$; $\eta^2 = 0.14$). Pairwise comparisons indicated a significant increase in alpha activity in the contralateral workspace compared to the ipsilateral workspaces (CTL- IPS = 0.07 μV , $p < .05$). There was a significant main effect of Workspace on electrode CP6 ($F_{(2, 46)} = 4.45$, $p < 0.05$; $\eta^2 = 0.16$). Pairwise comparisons indicated there was a significant increase in alpha activity in the contralateral workspace compared to the ipsilateral workspace (CTL – IPS = 0.1 μV , $p < .05$). There was no significant main effect of Workspace on electrode P4 ($F_{(2, 46)} = 2.267$, $p > 0.05$; $\eta^2 = 0.09$). There was also no significant main effect of Workspace on electrode P8 ($F_{(2, 46)} = 1.923$, $p > 0.05$; $\eta^2 = 0.08$).

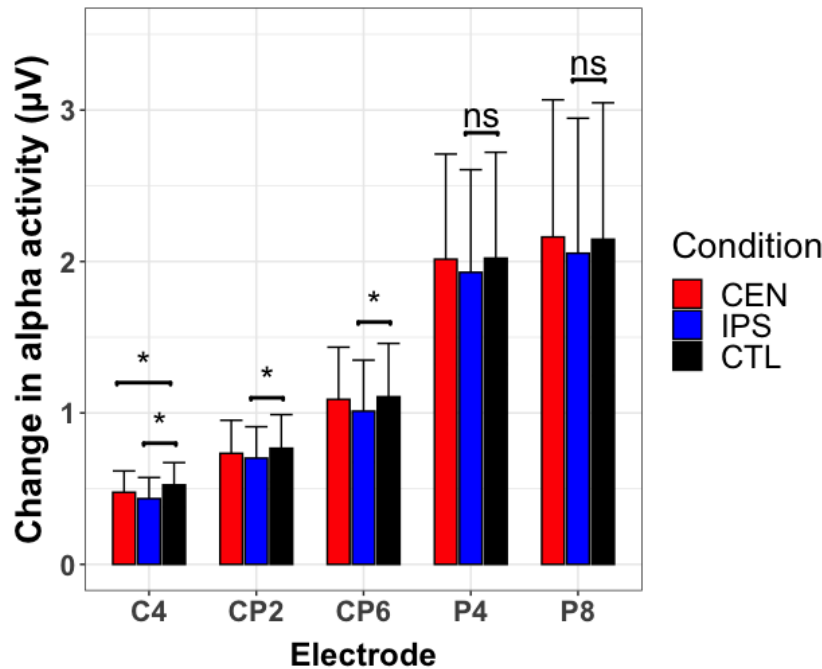


Figure 4.8. Average change in alpha activity across workspaces for selected electrodes.

Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated for workspace-related changes in beta activities for electrodes C4 ($\chi^2(2) = 9.99$, $p < .05$) and P8 ($\chi^2(2) = 14.69$, $p < .05$) but not CP2 ($\chi^2(2) = 4.542$, $p > .05$) and P4 ($\chi^2(2) = 3.15$, $p > .05$) hence a Greenhouse-Geisser correction was used where necessary. However, the assumption of sphericity was not violated for electrode CP6 ($\chi^2(2) = 4.94$, $p > .05$).

There was a significant main effect of Workspace on electrode C4 ($F_{(1.47, 33.69)} = 5.913$, $p < .05$; $\eta^2 = 0.21$). Pairwise comparisons indicated there was a significant decrease in beta activity in the ipsilateral workspace compared to the central workspace (CEN – CEN = $0.02 \mu V$, $p < .05$), and a significant increase in beta activity was also observed in the contralateral workspace compared to the ipsilateral workspace (CTL – IPS = $0.02 \mu V$, $p < .05$). There was a significant main effect of Workspace on electrode CP2 ($F_{(2, 46)} = 5.185$, $p < 0.05$; $\eta^2 = 0.18$). Pairwise comparisons indicated there was a significant increase in beta activity in the contralateral workspace compared to the ipsilateral workspace (CTL – IPS = 0.01 , $p < .05$) and central workspaces (CTL – CEN = 0.01 , $p < .05$). There was a significant main effect of Workspace on electrode P4 ($F_{(2, 46)} = 3.248$, $p < 0.05$; $\eta^2 = 0.12$). Pairwise comparisons indicated there was a significant increase in beta activity in the contralateral workspace compared to the ipsilateral workspace (CTL – IPS = $0.01 \mu V$, $p < .05$). There was a significant main effect of Workspace on electrode P8 ($F_{(1.345, 30.930)} = 3.944$, $p < 0.05 \mu V$; $\eta^2 = 0.15$). Pairwise comparisons indicated there was a significant decrease in beta activity in the contralateral workspace compared to the central workspaces (CTL- CEN = $-0.06 \mu V$, $p < .05$). There was no significant main effect of Workspace on electrode CP6 ($F_{(2, 46)} = 2.772$, $p > 0.05$; $\eta^2 = 0.11$).

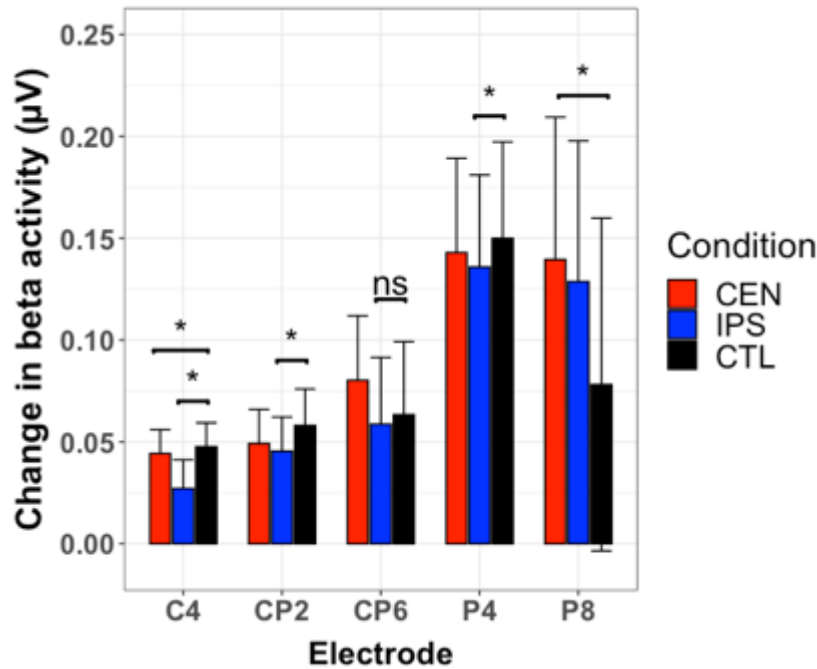


Figure 4.9. Average change in beta activity across workspaces for selected electrodes.

Based on visual inspection, we further analyzed changes in the theta activity within the lateral–frontal (F7 and F8) and medial–frontal (F3 and F4) electrodes and observed workspace effects in the F3 and F8 electrodes. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated for workspace-related changes in theta activities for electrodes F3 ($\chi^2(2) = 2.20$, $p > .05$) and F8 ($\chi^2(2) = 0.87$, $p > .05$). There was a significant main effect of Workspace on electrode F3 ($F_{(2, 46)} = 3.40$, $p < .05$; $\eta^2 = 0.13$). Pairwise comparisons indicated there was a significant decrease in theta activity in the ipsilateral workspace compared to the central workspace (CEN – IPS = $0.05 \mu V$, $p < .05$). There was also a significant main effect of Workspace on electrode F8 ($F_{(2, 46)} = 3.60$, $p < .05$; $\eta^2 = 0.14$). Pairwise comparisons indicated there was a significant

decrease in theta activity in the contralateral workspace compared to the central workspace (CTL – CEN = $-0.21 \mu\text{V}$, $p < .05$).

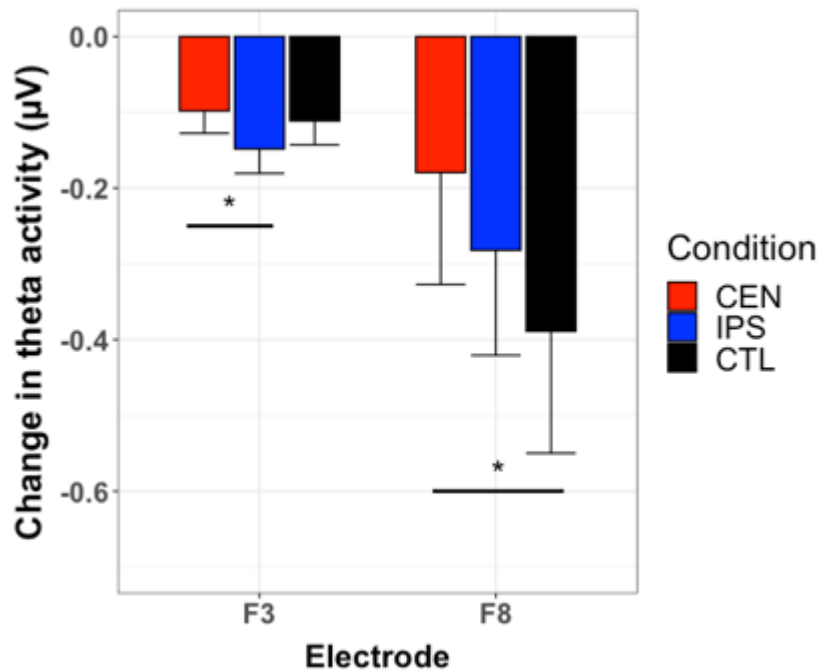


Figure 4.10. Average change in theta activity across workspaces for selected electrodes.

Discussion

Because of the existing evidence of visuomotor adaptation differences across workspace locations, the current study investigated how manipulating the external workspace locations modulates behavioral and neurophysiological changes during visuomotor adaptation. We found considerable changes in different behavioral parameters with respect to the different workspace locations the tasks were performed and associated neural correlates in the specific workspaces.

Behavioral changes

Our findings showed significant changes between the first and last trial blocks for all behavioral variables. Participants concurrently adapted to a visuomotor adaptation across all the three workspace locations based on the behavioral variables. Most studies examined the generalization of initial direction error across two of the three workspace locations investigated in this current study (Heuer & Hegele, 2011; Krakauer et al., 2000; Lei et al., 2013); consistent with our investigation which extended previous works by including a third workspace location while focusing on multiple movement parameters. Behavioral evidence shows visuomotor task setups influence generalization across different workspaces, depending on whether the visual and motor workspaces were combined (Heuer & Hegele, 2011; Lei et al., 2013; Vetter et al., 1999) or separated (Krakauer et al., 2000; Lei et al., 2013; Wang, 2008). For instance, according to Lei et al. (2013), visuomotor task performance did not generalize when the visual and motor workspaces were dissociated or in separate physical locations contrary to our current study. Separating the visual and motor workspace is likely to affect how reaches toward targets are planned and executed (Beurze et al., 2006; Blangero et al., 2007; Dijkerman & Milner, 1998; Khan et al., 2005) but may not necessarily translate to task performance.

Neurophysiological evidence

Different neural substrates are activated for both allocentric and egocentric processes for encoding target location for reaching movements despite their overlaps (Y. Chen et al., 2014). Both spatial representations are needed for optimal visuomotor control (Y. Chen, Monaco, & Crawford, 2018; Fiehler, Wolf, Klinghammer, & Blohm, 2014). Therefore, the strategy for encoding spatial representation across subjects can vary and

possibly affect inter-subject variability for different workspaces, which could be the reason for differences observed in the different movement parameters. We predicted that visuomotor adaptation to a visually rotated target would be associated with specific changes in brain oscillatory behaviors within the frontal, sensorimotor, and parietal areas of the brain when manipulating various workspace locations. Our findings supported this prediction. Specifically, a workspace location requiring midline crossing was associated with higher cortical processing compared to the central and ipsilateral workspace locations, consistent with the behavioral variables.

Differences in average alpha and beta activities were observed in the right parietal areas, ipsilateral to the arm performing the visuomotor task. While alpha activity is often associated with visual information processing (Bacigalupo & Luck, 2019), spatial attention, and cognitive processing (Pfurtscheller & Lopes da Silva, 1999), it could also reflect task-irrelevant suppression in other brain areas (Bacigalupo & Luck, 2019). Beta activity on the other hand is associated with motor control (Engel & Fries, 2010; Joundi, Jenkinson, Brittain, Aziz, & Brown, 2012; Pogosyan, Gaynor, Eusebio, & Brown, 2009) and encoding error feedback during trial-to-trial sensorimotor learning (Tan, Wade, & Brown, 2016). A decrease in beta-band oscillations (i.e., movement-related beta desynchronization) in the sensorimotor regions indicates movement-related activities (Pfurtscheller & Lopes da Silva, 1999; Pfurtscheller, Zalaudek, et al., 1998; Salmelin & Hari, 1994; Stancak & Pfurtscheller, 1995). Workspace related differences of alpha and beta activities in the task-relevant brain areas (mainly the right central parietal cortex) could be associated with its role visuospatial attention processing as reported in previous neuroimaging studies (Capotosto, Corbetta, Romani, & Babiloni, 2012; Malhotra, Coulthard, & Husain, 2009; Szczepanski, Konen,

& Kastner, 2010). Based on the role of the right parietal region, there is a possibility of additional spatial processing demand when crossing the midline contributing to the observed workspace- related differences in both alpha and beta activities. A visual inspection of the alpha topo maps shows a strong activity in the right occipital region (i.e., O2 electrode) further supporting the role of possible spatial visuo-spatial attention. Furthermore, the contralateral workspace requires crossing one's midline, a workspace where the ipsilateral hand is usually preferred; this could create a discrepancy for the brain and might need to consolidate the new task performance.

We also observed workspace effects in prefrontal theta effects in the F3 and F8 electrodes, which serves as a neural signature for cognitive control (Zamorano et al., 2020). The prefrontal cortex relies on experience and routines for decision making (Cavanagh & Frank, 2014). An increase in lateral prefrontal theta activity reflects proactive cognitive control (i.e., modifying responses based on experience during goal-directed tasks) (Ryman et al., 2018; Zamorano et al., 2020). Conversely, an increase medial frontal theta activity reflects reactive cognitive control such as error monitoring and conflict detection (Cavanagh & Frank, 2014; Clayton, Yeung, & Cohen Kadosh, 2015). We used a 32-electrode EEG system which makes brain localization very difficult. However, the workspace effects in the right lateral–frontal and medial–frontal regions could reflect differences in cognitive strategies in the respective workspaces.

The prefrontal cortex is also part of a network responsible for top-down spatial attentional control (Banich et al., 2009; Buschman & Miller, 2007; Siltan et al., 2010). Spatial attention, attending to visual information within the environment, can be

intentional or unintentional (head or eye movements) (Hopfinger et al., 2000). The cognitive control of intentional spatial attention involves disengagement and reorienting focus to a new stimulus forming a part of the top-down attentional processing (Posner & Petersen, 1990). The top-down attentional processes are supported by a network of cortical (i.e., superior frontal cortex, inferior parietal cortex, superior temporal cortex) and subcortical structures (posterior cingulate cortex and insula) (Hopfinger et al., 2000). During visuomotor adaptation, the top-down processes originating from the frontal to the posterior areas inhibit existing motor plans to integrate new plans (Gentili et al., 2015). Voluntarily attending to the visual target improves target localization and performance (Bashinski & Bacharach, 1980; Posner, 1980; Tong, 2003). The contralateral workspace location creates a more challenging response conflict for accurate target localization, requiring more attention to explain the space-related differences in the prefrontal theta activities. The workspace related prefrontal theta activities could reflect the response of the frontal networks receiving inputs from the anterior cingulate cortex to counteract the challenging response conflict (Gentili et al., 2015; Procyk, Amiez, Quilodran, & Joseph, 2007; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004) of the contralateral workspace.

Limitation

Our current study used a 32-electrode EEG system, making it challenging to perform source localization analysis for specific brain areas. Future studies should consider an EEG system with more channels to perform source localization for specific brain regions. Furthermore, we did not investigate event-related EEG activity but rather an overall cortical activity for each workspace however, our behavioral analysis focused on performance differences between the first and last blocks. There was no test of after-effects to assess the persistence of adaptation,

hence we cannot conclude if this adaptation was mainly effector dependent (i.e., model free learning) or independent (i.e., involving the creation of an internal model). Finally, we focused on performance rather than learning; hence results were presented in the lights of performance.

Conclusion

In summary, participant adapted to the rotational bias across all workspace locations. Corresponding neural measures indicated workspace related changes, with the biggest differences between contralateral and ipsilateral workspaces consistent with the observed pattern in behavioral results. The observed neurophysiological patterns were mainly in the right central and parietal areas – brain areas involved in spatial processing. This study brings to light the effect of workspace locations on visuomotor control on a comprehensive list of movement parameters.

CHAPTER 5. GAZE- CENTERED SPATIAL CODING OF VISUAL REACH TARGET DURING VISUOMOTOR ADAPTATION- WORKSPACE EFFECTS

Introduction

People direct gaze at objects in our environment when performing everyday tasks (Hayhoe & Ballard, 2005; Land, 2006; Land & Hayhoe, 2001; Neggers & Bekkering, 1999; Voudouris, Smeets, & Brenner, 2012, 2016). Gaze direction is often used when planning movements (Adam, Buetti, & Kerzel, 2012) to precisely localize targets for goal-directed reaches (Brenner & Smeets, 1997, 2011; Oostwoud Wijdenes, Brenner, & Smeets, 2011; Prablanc et al., 1986). Reaching a target requires accurate spatio-temporal coordination of movements of the eyes and hand (Rentsch & Rand, 2014) and reaching accuracy is improved by aligning gaze on the target (Abrams et al., 1990; Prablanc et al., 1979; Prablanc et al., 1986) which can be perceived via foveal vision (Gaveau et al., 2008; Lunenburger, Kutz, & Hoffmann, 2000; Prablanc et al., 1986). Saccades made toward the target during reaching provide the fovea with new information of interest to update the target's internal representation (Prablanc et al., 1986) needed for movement control.

Remember that during standard visuomotor adaptation protocols, people direct their gaze toward the cursor, representing hand position, at the initial phase of learning and toward the target later on during adaptation (Rentsch & Rand, 2014). In this case, visual feedback of the cursor and target location influences strategies in adapting to a visuomotor rotation task (Rand & Rentsch, 2017). Even though gaze anchoring on the target correlates with adaptation patterns (Rand & Rentsch, 2016, 2017; Rentsch & Rand, 2014), it may not play a significant role in visuomotor adaptation (Gouirand, Mathew, Brenner, & Danion, 2019) aside from tracking

reaching accuracy (Gouirand et al., 2019; Rand & Rentsch, 2016; Rentsch & Rand, 2014).

Visuomotor adaptation is driven by sensory prediction errors (i.e., a mismatch between expected and observed movement consequences) (Diedrichsen, Hashambhoy, Rane, & Shadmehr, 2005; Gaveau, Prablanc, Laurent, Rossetti, & Priot, 2014; Shadmehr, Smith, & Krakauer, 2010) and can happen regardless of eye movements (Gouirand et al., 2019). Gouirand et al. (2019) showed that restricting eye movements to fixate on peripheral target during visuomotor tracking of a moving target still led to adaptation, just as for unrestricted eye movement conditions. Individuals adapted to the applied rotation by updating the hand movement through visual feedback of cursor movements which was not associated with movements of the eyes (Gouirand et al., 2019). Since altering gaze direction, thus eye movements (de Brouwer, Albaghdadi, Flanagan, & Gallivan, 2018), reflects an explicit component (cued knowledge of applied offset) of visuomotor adaptation (Bromberg, Donchin, & Haar, 2019; Rand & Rentsch, 2015), needed for aiming accurately toward targets (Benson, Anguera, & Seidler, 2011; Mazzoni & Krakauer, 2006; Taylor & Ivry, 2011), online feedback of target location may be key to explicit control during visuomotor adaptation. Thus, removal of target location during movement might impair such adaptation.

The motor system relies on visual information to encode the spatial features of the environment (i.e., target location) for movement control (Sarlegna & Sainburg, 2009) to perform a visuomotor adaptation task (Thaler & Todd, 2010). In a cursor transformation adaptation task, tracking the unseen hand movement only occurs via the rotated cursor feedback on the screen, and requires some egocentric processing (Thaler & Todd, 2010), whereas moving a pen toward an endpoint away from the target due to rotation of visual feedback requires allocentric cues of

target location (Thaler & Todd, 2010). The visual, thus allocentric information of target location and egocentric feedback of the moving hand produces adaptive gaze behaviors (Rand & Rentsch, 2016; Rentsch & Rand, 2014). However, in this case the eyes and hand are not aligned. When targets are presented during simple pointing tasks, then removed before movement onset (i.e., Remembered targets), the distribution of endpoint reaches show an ellipsoid pattern, increasing pointing errors along gaze direction (Admiraal, Keijsers, & Gielen, 2003) and support the idea that movement endpoint is planned separately for extent and direction (Flanders, Tillery, & Soechting, 1992; Gordon, Ghilardi, & Ghez, 1994). Directional adjustments for reaching movements associated with inputs from gaze direction (Admiraal et al., 2003; Hondzinski & Cui, 2006) allow direct comparisons between hand and target location (Beggs & Howarth, 1972; Carlton, 1981). The close alignment between the eyes and hand in these latter cases vary from those involved in visuomotor adaptation tasks. Whether adaptation may differ for visuomotor adaptation performances achieved with actual versus remembered target locations requires further investigation.

One research goal of the present study was to assess whether visual feedback of the movement trajectory (egocentric cues) and movement endpoint feedback (allocentric cues) was required for visuomotor adaptation to occur or whether only visual feedback of movement trajectory during performance of visuomotor adaptation task will suffice. Another goal was to determine the effect of visual feedback on eye movements/gaze direction used. Accounting for potential visual feedback and gaze direction influences during visuomotor adaptation could be useful in inferring the time course of learning a visuomotor adaptation task and provide more insight into gaze strategies used. To test our research goals, we examine visuomotor adaptation

and the potential contributions of gaze direction using remembered and visible targets. We include various workspace locations to further assess gaze behavior and spatial processing strategies under different contexts. We hypothesized that spatial parameters such as initial direction error and pathlength would be greater during performances using remembered targets than visible targets, due the absence of terminal feedback in the former case. We also hypothesized that gaze patterns/strategies would differ between types of visual feedback. Lastly, since gaze is often fixated on the target later during visuomotor adaptation (Rand & Rentsch, 2016), we predicted that the absence of the visual feedback of the target would alter the course of adaptation.

Methods

Participants: Twenty-four young adults (age, 23.33 ± 5.34 yrs, mean \pm S.D., all right-handed; 14 Females) with normal or corrected-to-normal vision were recruited for the study. Participants were randomly assigned to one of two experimental groups; Visible target and Remembered targets. All participants were right-hand dominant according to the Edinburgh Handedness Inventory (Oldfield, 1971) with a laterality quotient of at least 0.65 or higher. An investigator communicated the purpose of the study to all participants and answered any questions about the study after they read signed the informed consent for the study. The experimental protocol was approved by the Institutional Review Board for Human Subjects Research at Louisiana State University.

Task: The setup included a horizontal digitizer tablet as the workspace connected to a vertical monitor for visual feedback. The monitor was situated in front of the participants;

however, the position of the horizontal tablet was moved depending on the workspace condition. Participants sat in front of the monitor and digitizer tablet after donning a mobile eye-tracker that resembles large eyeglasses to track gaze during visuomotor performances (see description below). Calibration of the eye tracker accounted for gaze position on the vertical monitor, where targets were presented, and pen movements were shown as cursor movement in real-time during task performances. Participants were then asked to draw a line from a start circle (a black circle in the center of the monitor; 0.5 cm diameter) to targets (a black circle 9 cm away from the start position; 0.5 cm diameter) located in one of 4 quadrants as fast and as accurately as possible. Each trial was composed of a series center out movement with the stylus on a tablet to one of 12 targets located in four quadrants (see figure 3.1; one target appears at a time).

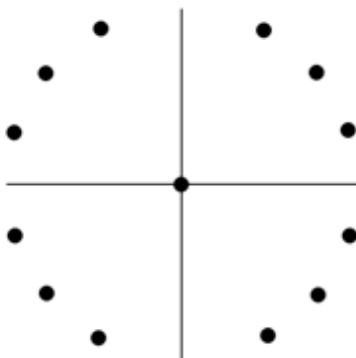


Figure 5.1. Target (black dots) arrangement in each quadrant with start circle in the middle.

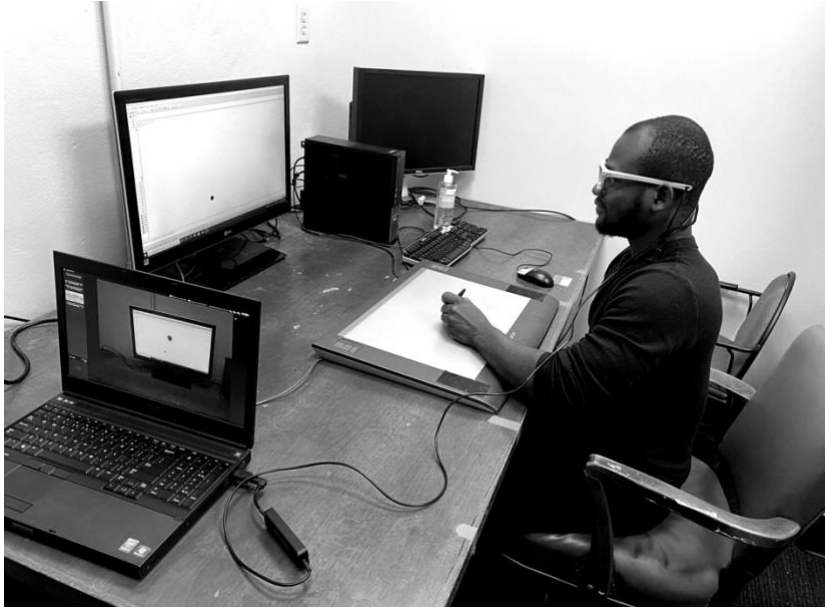


Figure 5.2. Experimental set up

Procedure: Two groups were formed and depended on whether the visual feedback of the target remained visible through movement trajectory (Visible target) or disappeared at movement onset (Remembered target). In each group participants first performed a familiarization task at the beginning of the experiment, where the distance from the center start circle to the targets (4 cm) and the diameter of the circles (3.5 cm) used varied from experimental conditions. After the start circle appeared, participants moved the pen tip within the start circle. After the pen tip entered the start circle, the start circle disappeared, and the target circle appeared. Depending on the experimental group, the target could remain on the screen throughout the movement trajectory or disappear 0.5 s after its appearance. Participants moved the pen tip as quickly and accurately as possible to the Visible or Remembered target location. Once the participant moved the pen tip into the target (9 cm from the center of the target), a new trial started.

Depending on the session (see Table 5.1), the online visual feedback of the movement trajectory was unrotated or rotated 45° clockwise. Four familiarization trials were performed prior to the start of the experiment. Participants completed drawing tasks in five sessions to either Remembered (REM) or Visible targets (VIS), depending on assigned group. The initial baseline session and final aftereffect session involved non-distorted, thus unrotated visual feedback to determine the existence of aftereffects of adaptation. The baseline (pre-test), training, and retention (post-test) sessions involved distorted visual feedback to determine the existence of acquisition, retention, and workspace transfer effects. Training trials occurred only in the central workspace, while trials for all other sessions were performed in each of the three workspace locations.

Table 5.1. Experimental progression and number of trials

Group	Baseline unrotated			Baseline rotated			Training rotated	Retention rotated			After-effects unrotated		
	CEN	IPS	CTL	CEN	IPS	CTL	CEN	CEN	IPS	CTL	CEN	IPS	CTL
Visible target	4	4	4	8	8	8	120	8	8	8	4	4	4
Remembered target	4	4	4	8	8	8	120	8	8	8	4	4	4

Note: CEN = central workspace, IPS = ipsilateral workspace, CTL = contralateral workspace

Data collection: A WACOM (Intuos3 12 x19) digitizer tablet connected to a PC with a (50x30cm) monitor was used for collecting pen recordings and providing visual feedback of pen

movements. A normal looking electronic non-inking pen (WACOM ZP-130) was used to make drawings on the tablet. The sampling rate of the X- and Y- position of pen tip is 200 Hz and spatial resolution was 0.0005 cm in X- and Y- direction. An SMI mobile binocular eye tracker (SMI, Teltow, Germany) was used to record and track eye movements and gaze contributions at 60 Hz.

Data processing: The pen tip data recordings were processed with a custom-made program developed in MATLAB (MathWorks Inc., Natick, MA, USA). The position signals were filtered using a Butterworth 4th order dual pass filter with a cut-off frequency of 16 Hz. The movement segments were parsed using the 5% of the peak velocity criterion in the velocity profile to determine movement onset (i.e., start) and offset (i.e., end). Frame-by-frame review of point of gaze video data were manually recorded to determine eye movement variables of interest using BeGaze software (SMI, Teltow, Germany). Variables of interest included eye and hand reaction, movement, and response times (calculations are described below).

Dependent Variables

The following dependent variables were estimated from the Movalyzer:

- Initial direction error-IDE (degrees): the angle between the vector from the center of the home circle position and the center of target position and the vector between the onset location of the movement and the location at 80 ms into movement.
- Movement time-MT (s): The stroke duration between the onset and offset of the movement.

- Pathlength-PL (cm): Cumulative length of the movement trajectory between onset and offset of the movement.
- Normalized jerk-NJ (unitless): The rate of change of acceleration normalized for stroke size and duration (cf. Van Gemmert, Teulings, & Stelmach, 1998).
- Resultant velocity-RV (cm/s): Square root of the sum of the squared velocity in the x- and y-direction between onset and offset of the movement.

The following dependent variables were estimated from the Eye tracking system:

- Eye and Hand reaction time-RT (s): The time between the frame of target appearance and the first discernable frame of onset of movement of the point of gaze and hand
- Eye and Hand movement time-MT (s): The time between the first discernable frame of onset and offset of movement of the point of gaze and hand
- Eye and Hand response time-RST (s): The time between the frame of target appearance and the first discernable frame of movement offset of the point of gaze and hand.

Movement time from the Movalyzer and the eye tracking system measure the same construct. As mentioned previously, the hand movement time from the Movalyzer was based on the 5% of the peak velocity criterion, whereas movement time for gaze and hand from the eye tracking video was based the first (onset) and last (offset) frames of gaze or hand movement, respectively.

Statistical analysis: All data were checked for normal distribution and sphericity, using a Shapiro-Wilk's test and Mauchly's test, respectively. Greenhouse-Geisser corrections were used

for violations of sphericity. Since most of the data were skewed, the median was computed and used for the ANOVAs (Muslimovic, Post, Speelman, & Schmand, 2007; Zemmar et al., 2014). A 3 Workspace (CEN, IPS, CTL) x 2 Group (VIS/REM) x 2 Test (post-test - pre-test training test) mixed factors ANOVA was performed on movement parameters with workspace and test as within subject factors and target condition as between subject factors for rotated (after-effects) and unrotated (retention) tests, independently. If there was a significant interaction, a Bonferonni Post-hoc test was done, and the significant level for all tests was set at 0.05. Finally, we examined coupling between temporal variables of the eye and hand via correlation analysing using the Pearson correlation coefficient. We only present significant outcomes in results for brevity. See appendix B for these result details.

Results

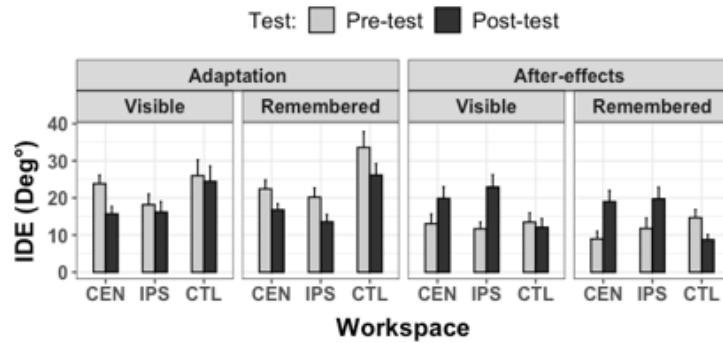
Behavioral variables from Movalyzer

IDE and PL

Adaptation: Significant Group differences observed only for PL revealed a longer PL for REM compared to VIS (VIS – REM = -0.73cm, $F_{(1,22)} = 5.77$, $p < 0.05$; $\eta^2 = 0.21$). Significant main effects of Test on IDE ($F_{(1,22)} = 10.909$, $p < 0.05$; $\eta^2 = 0.33$) and PL ($F_{(1,22)} = 55.471$, $p < 0.05$; $\eta^2 = 0.72$) indicated that IDE and PL reduced significantly from pre-test to post-test (IDE: post-test - pre-test = -5.23°, see Figure 5.3; PL: post-test - pre-test = -1.31cm, see Figure 5.4). Significant effects of Workspace on IDE ($F_{(1.57, 34.42)} = 17.902$, $p < 0.05$; $\eta^2 = 0.45$) and PL ($F_{(2, 44)} = 27.96$, $p < 0.05$; $\eta^2 = 0.56$) revealed that IDE and PL were significantly greater in the contralateral workspace compared to the central (IDE: CTL – CEN = 7.86°, $p < 0.05$; PL: CTL –

CEN = 0.78 cm, $p < 0.05$) and ipsilateral workspaces (IDE: CTL – IPS = 10.52, $p < 0.05$; PL: CTL – IPS: 1.31cm, $p < 0.05$). Only PL was longer in the central compared to the ipsilateral (CEN – IPS: 0.53cm, $p < 0.05$) workspace.

After-effects: Significant main effects of Test on IDE (post-test - pre-test = 4.53° , $F_{(1,22)} = 4.92$, $p < 0.05$; $\eta^2 = 0.18$) and PL (post-test - pre-test = 0.72 cm, $F_{(1,22)} = 12.34$, $p < 0.05$; $\eta^2 = 0.36$) were observed such that post-test values exceeded pre-test values. There were two-way interactions of Workspace x Test for IDE ($F_{(2,44)} = 8.62$, $p < 0.05$; $\eta^2 = 0.28$) and PL ($F_{(2,44)} = 15.78$, $p < 0.05$; $\eta^2 = 0.42$). Post-hoc tests indicated a significant increase in IDE and PL from pre-test to post-test in the central workspace (IDE: post-test - pre-test = 7.96° , $p < 0.05$; $\eta^2 = 0.24$; PL: post-test - pre-test = 0.58 cm, $p < 0.05$; $\eta^2 = 0.22$). A similar pattern was observed in the ipsilateral workspace for IDE (post-test - pre-test = 12.52° , $p < 0.05$; $\eta^2 = 0.3$) and PL (post-test - pre-test = 1.38 cm, $p < 0.05$; $\eta^2 = 0.49$) (see Figure 5.3 and 5.4).



CEN = central workspace, IPS = ipsilateral workspace, CTL = contralateral workspace

Figure 5.3. Means of median values for initial direction error (IDE) with standard errors from pre-test to post-test as a function of workspace and group.

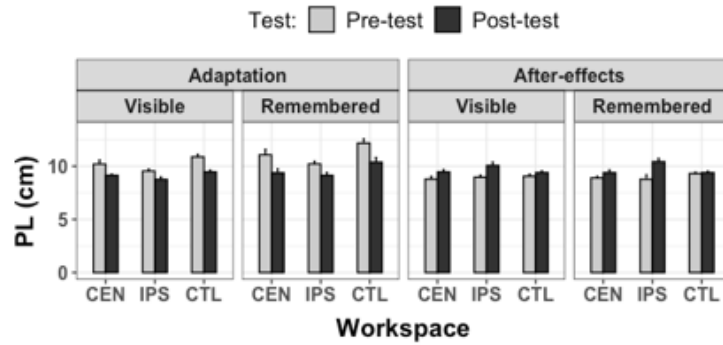


Figure 5.4. Means of median values for Pathlength (PL) with standard errors from pre-test to post-test as a function of workspace and group.

MT and RV

Adaptation: There were main effects of Test on MT (post-test - pre-test = 675.38 ms, $F_{(1,22)} = 58.30$, $p < 0.05$; $\eta^2 = 0.73$) and RV (post-test - pre-test = 2.12 cm/s, $F_{(1,22)} = 25.62$, $p < 0.05$; $\eta^2 = 0.54$) with smaller MT values and larger RV values observed at post-test (see Figure 5.5 and 5.6, respectively). There was also main effect of Workspace on MT ($F_{(2,44)} = 12.62$, $p < 0.05$; $\eta^2 = 0.36$) such that MT was significantly greater in the contralateral than the ipsilateral (CTL – IPS = 301.30 ms, $p < 0.05$) as well as the central (CTL – CEN = 186.82 ms, $p < 0.05$) workspaces. A significant three-way interaction of Group x Workspace x Test for RV was observed ($F_{(1,22)} = 4.58$, $p < 0.05$; $\eta^2 = 0.17$). Post-hoc tests indicated RV of the Visible group was significantly greater from pre-test to post-test when working in the contralateral space (post-test - pre-test = 1.79 cm/s, $p < 0.05$; $\eta^2 = 0.32$). For the Remembered target group, there was a significant increase in RV from pre-test to post-test in all three workspaces; central (post-test - pre-test = 2.63 cm/s,

$p < 0.05$; $\eta^2 = 0.50$), ipsilateral (post-test - pre-test = 3.62 cm/s, $p < 0.05$; $\eta^2 = 0.49$) and contralateral (post-test - pre-test = 2.04 cm/s, $p < 0.05$; $\eta^2 = 0.38$) workspaces (see Figure 5.6).

After-effects: A significant main effect of Test on MT (post-test - pre-test = 248.96 ms, $F_{(1,22)} = 6.31$, $p < 0.05$; $\eta^2 = 0.22$) and RV (post-test - pre-test 1.72 cm/s, $F_{(1,22)} = 19.63$, $p < 0.05$; $\eta^2 = 0.47$) indicated lower values at post-test than pre-test for MT and corresponding greater values for RV (see Figure 5.5 and 5.6). A significant Workspace effect on MT ($F_{(2,44)} = 4.73$, $p < 0.05$; $\eta^2 = 0.18$) and RV ($F_{(2,44)} = 3.56$, $p < 0.05$; $\eta^2 = 0.14$) indicated lower MT in the central compared to the contralateral workspace (CTL – CEN = 132.03 ms, $p < 0.05$). MT was also lower in the central than the ipsilateral workspace (CEN – IPS = -175.47 ms, $p < 0.05$), while RV was greater in the central compared to the ipsilateral workspace (CEN – IPS = 0.55 cm/s, $p < 0.05$). The significant two-way interaction of Workspace x Test on MT ($F_{(1,22)} = 4.34$, $p < 0.05$; $\eta^2 = 0.17$) revealed that MT was significantly reduced from pre-test to post-test in the central (post-test - pre-test = 222.08 ms, $p < 0.05$; $\eta^2 = 0.19$) and contralateral workspaces (post-test - pre-test = 431.56 ms, $p < 0.05$; $\eta^2 = 0.33$). The significant two-way interaction for Group x Test on RV ($F_{(1,22)} = 10.74$, $p < 0.05$; $\eta^2 = 0.33$) showed that RV significantly increased from pre-test to post-test for the Remembered target group (post-test - pre-test = 3.00 cm/s, $p < 0.05$; $\eta^2 = 0.57$) and this value at post-test was larger than the Visible target group (REM - VIS = 0.08 cm/s, $p < 0.05$; $\eta^2 = 0.09$).

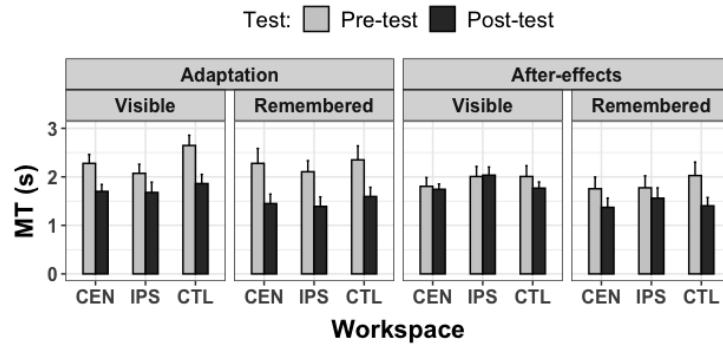


Figure 5.5. Means of median values for movement time (MT) with standard errors from pre-test to post-test as a function of workspace and group.

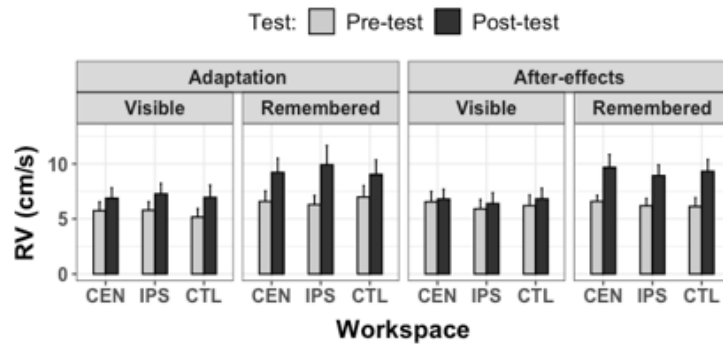


Figure 5.6. Means of median values for resultant velocity (RV) with standard errors from pre-test to post-test as a function of workspace and group.

NJ

Adaptation: There were main effects of Test (post-test - pre-test = -1172.79, $F_{(1,22)} = 11.65$, $p < 0.05$; $\eta^2 = 0.35$) and Workspace ($F_{(2,44)} = 3.53$, $p < 0.05$, $p = 0.038$; $\eta^2 = 0.14$) on NJ. Smaller NJ values from pre-test to post-test indicate smoother movements (see

Figure 5.7). Non-significant post-hoc tests indicated NJ did not vary significantly between workspace conditions (Figure 5.7).

After-effect: There was a significant main effect for Test on NJ (post-test - pre-test = - 756.67, $F_{(1,22)} = 12.66$, $p < 0.05$; $\eta^2 = 0.37$). Smaller values, thus smoother movements, existed from pre-test to post-test (see Figure 5.7).

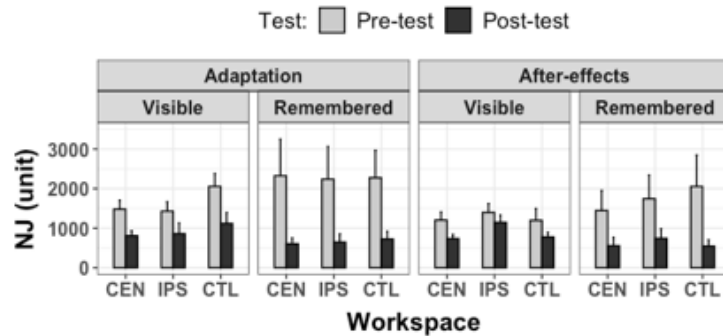


Figure 5.7. Means of median values for normalized jerk (NJ) with standard errors from pre-test to post-test as a function of workspace and group.

Behavioral variables from Eye tracking system

Eye and Hand RT

Adaptation: A significant main effect of Group on Eye RT (VIS - REM = 0.06 s, $F_{(1,22)} = 5.19$, $p < 0.05$; $\eta^2 = 0.19$) revealed that the REM group recorded a shorter RT compared to the VIS group. Significant main effects of Test on Eye RT (post-test - pre-test = - 0.04s, $F_{(1,22)} = 4.34$, $p < 0.05$; $\eta^2 = 0.17$) and Hand RT (post-test - pre-test = - 0.04s, $F_{(1,22)} = 5.11$, $p < 0.05$; $\eta^2 = 0.19$) revealed significant reductions for each at post-test. The significant two-way interaction for Workspace x Test on Hand RT ($F_{(2,44)} = 3.87$, $p < 0.05$; $\eta^2 = 0.15$) revealed a significant decrease

in Hand RT for the central (post-test - pre-test = - 0.06s, $p < 0.05$; $\eta^2 = 0.17$) and contralateral workspace (post-test - pre-test = - 0.06s $p < 0.05$; $\eta^2 = 0.27$).

After-effects: A significant two-way interaction of Group x Test on Eye RT ($F_{(1,22)} = 2.05$, $p < 0.05$; $\eta^2 = 0.17$) and Hand RT ($F_{(1,22)} = 7.29$, $p < 0.05$; $\eta^2 = 0.25$) indicated significant decreases in Eye RT (post-test - pre-test = - 0.05s, $p < 0.05$; $\eta^2 = 0.17$) and Hand RT (post-test - pre-test = - 0.07s, $p < 0.05$; $\eta^2 = 0.26$) for the Remembered target group (see Figure 5.8 and 5.9). The Remembered target group reacted faster than the Visible target group for the eyes (REM - VIS = - 0.06 s, $p < 0.05$; $\eta^2 = 0.14$) and hand (REM - VIS = - 0.11 s, $p < 0.05$; $\eta^2 = 0.30$).

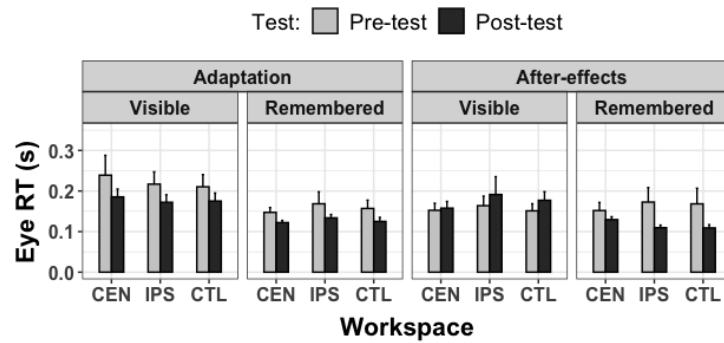


Figure 5.8. Means of median values for eye reaction time (Eye RT) with standard errors from pre-test to post-test as a function of workspace and group.

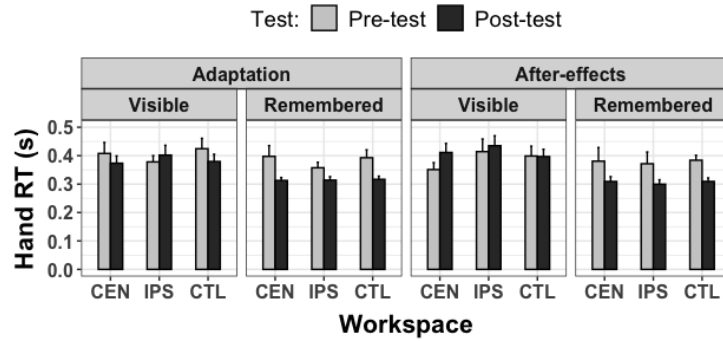


Figure 5.9. Means of median values for hand reaction time (Hand RT) with standard errors from pre-test to post-test as a function of workspace and group.

Eye and Hand MT

Adaptation: A significant main effect of Test on Eye MT (post-test - pre-test = - 0.44s, $F_{(1,22)} = 23.04$, $p < 0.05$; $\eta^2 = 0.51$) and Hand MT (post-test - pre-test = - 0.51s, $F_{(1,22)} = 37.72$, $p < 0.05$; $\eta^2 = 0.63$) showed that MT decreased from pre-test to post-test (see Figure 5.10 and 5.11). The significant Workspace effect on Eye MT ($F_{(2,44)} = 14.45$, $p < 0.05$; $\eta^2 = 0.40$) and Hand MT ($F_{(2,44)} = 23.97$, $p < 0.05$; $\eta^2 = 0.53$) indicated a greater MT in the contralateral workspace compared to the ipsilateral workspace for eyes (CTL – IPS = 0.33s, $P < 0.05$) and hand (CTL – IPS = 0.30s, $P < 0.05$). Hand MT was also greater in the contralateral than the central workspace (CTL – CEN = 0.16s, $P < 0.05$) and the central than ipsilateral workspace (CEN – IPS = 0.14s, $P < 0.05$). A significant two-way interaction of Workspace x Test on Eye MT ($F_{(2,44)} = 10.62$, $p < 0.05$; $\eta^2 = 0.33$) indicated that although it decreased in all three workspaces from pre-test to post-test, it decreased the most for the contralateral workspace (see Figure 5.10).

After-effects: There was a significant main effect of Workspace on Hand MT ($F_{(2,44)} = 4.54, p < 0.05; \eta^2 = 0.17$). Post-hoc tests revealed Hand MT was significantly smaller, thus shorter, in the central compared to the ipsilateral workspace (CEN – IPS = - 0.12s, $P < 0.05$).

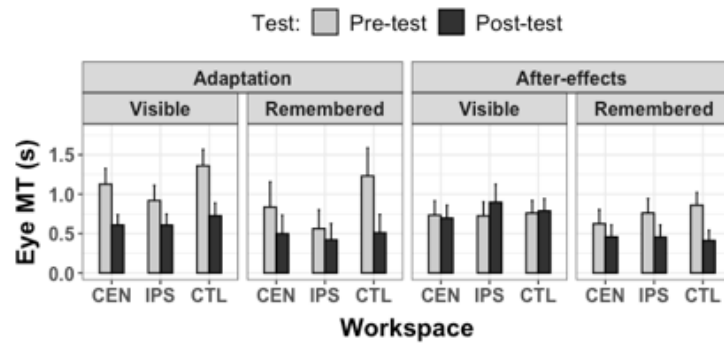


Figure 5.10. Means of median values for eye movement time (Eye MT) with standard errors from pre-test to post-test as a function of workspace and group.

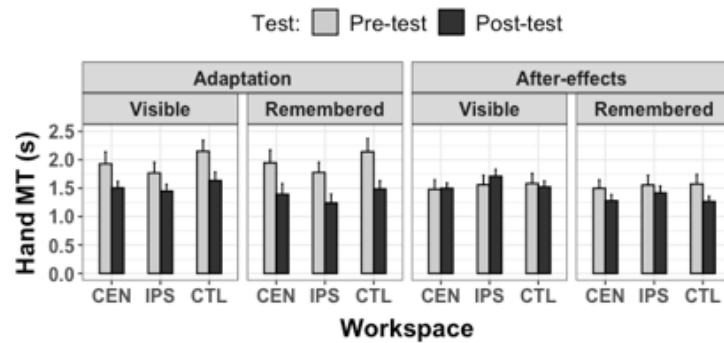


Figure 5.11. Means of median values for hand movement time (Hand MT) with standard errors from pre-test to post-test as a function of workspace and group.

Eye and Hand RST

Adaptation: A significant main effects of Test on Eye RST (post-test - pre-test = - 0.49s, $F_{(1,22)} = 24.80$, $p < 0.05$; $\eta^2 = 0.53$) and Hand RST (post-test - pre-test = - 0.57s, $F_{(1,22)} = 11.43$, $p < 0.05$; $\eta^2 = 0.63$) indicated both reduced significantly from pre-test to post-test (see Figure 5.12 and 5.13). We also observed significant main effects of Workspace on Eye RST ($F_{(2,44)} = 11.87$, $p < 0.05$; $\eta^2 = 0.35$) and Hand RST ($F_{(2,44)} = 26.29$, $p < 0.05$; $\eta^2 = 0.54$) which showed that Eye RST and Hand RST were significantly greater, thus produced a slower response in the contralateral workspace than the ipsilateral and central (Eye RST: CTL – IPS = 0.30s, $P < 0.05$; CTL – CEN = 0.18s, $p < 0.05$; Hand RST: CTL – IPS = 0.33s, $P < 0.05$; CTL – CEN = 0.19s, $p < 0.05$). The significant two-way interaction for Workspace x Test on Eye RST ($F_{(2,44)} = 8.54$, $p < 0.05$; $\eta^2 = 0.28$) and Hand RST ($F_{(2,44)} = 4.39$, $p < 0.05$; $\eta^2 = 0.17$) indicated significant decreases in responses from pre-test to post-test for each workspace with the largest change for contralateral workspace (see Figure 5.12 and 5.13).

After-effects: A significant main effect of Workspace on Hand RST ($F_{(2,44)} = 5.79$, $p < 0.05$; $\eta^2 = 0.21$) revealed Hand RST was significantly shorter in the central than the ipsilateral workspace (CEN – IPS = - 0.15s, $P < 0.05$). A significant two-way interaction for Group x Test on Eye RST ($F_{(1,22)} = 4.42$, $p < 0.05$; $\eta^2 = 0.17$) indicated that Eye RST was shorter from pre-test to post-test for the Remembered target group (post-test - pre-test = - 0.37s, $p < 0.05$; $\eta^2 = 0.21$) (see Figure 5.12), which was also shorter at post-test than the Visible target group (REM – VIS = - 0.45 s, $p < 0.05$; $\eta^2 = 0.13$).

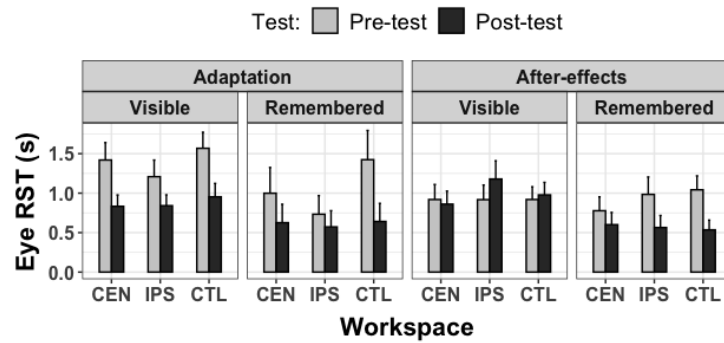


Figure 5.12. Means of median values for eye response time (Eye RST) with standard errors from pre-test to post-test as a function of workspace and group.

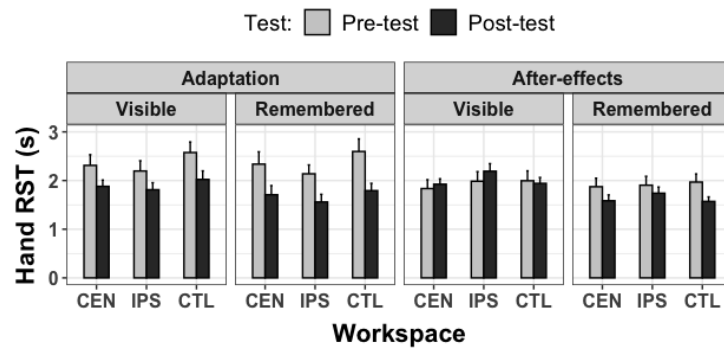


Figure 5.13. Means of median values for hand response time (Hand RST) with standard errors from pre-test to post-test as a function of workspace and group.

Figures 5.14 and 5.15 show adaptive trial-to-trial changes for eye and hand movement and response times, respectively, for each target group. Values and variability decreased with practice as shown at the later stages of adaptation (to the right of the black dashed segment).

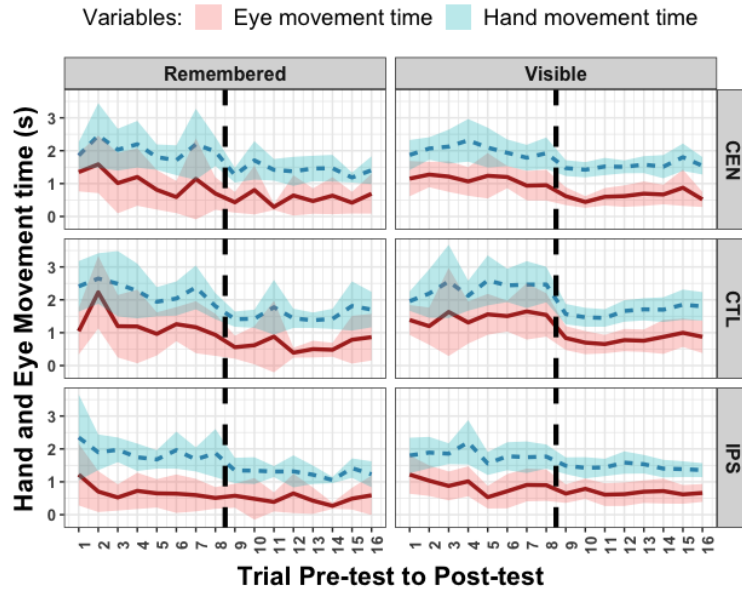


Figure 5.14. Adaptive changes of trial-to-trial eye and hand movement times for pre-test to post-tests.

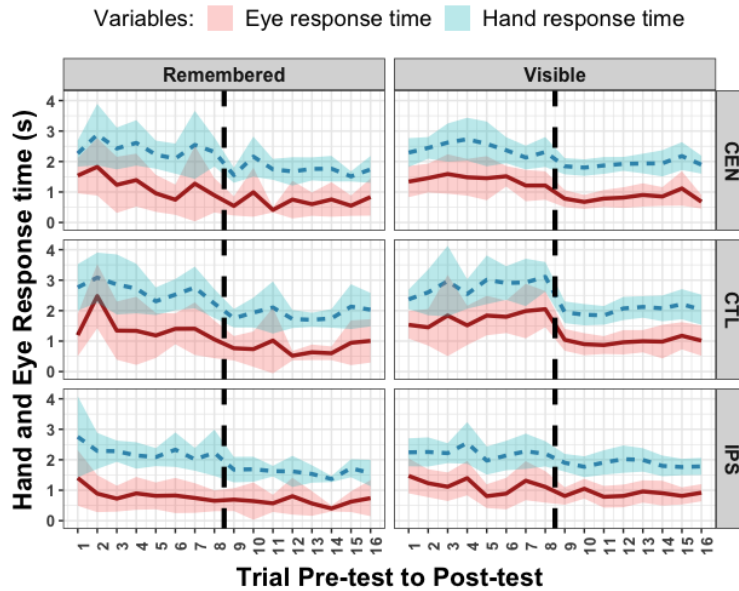


Figure 5.15. Adaptive changes of trial-to-trial eye and hand response time for pre-test to post-tests.

Eye-Hand coordination based on key temporal variables

We examined coupling between the eyes and hand through correlation analyzes. We observed significant correlations between the eyes and hand for RT, MT, and RST for each group ($p < 0.05$, see Figure 5.16). Values below and right of the unity line indicate smaller, thus slower values for variables associated with the hand than the corresponding variable for the eyes. Notice the greater correlation for RT in the Visible compared to Remembered target groups (bottom panels of Figure 5.16). Although participants reacted slower with initiating hand movement than movement of the eyes, RT of the hand seemed to follow RT of the eyes better when the target remained visible throughout the trial. Upper and middle panels of Figure 5.16 also revealed significantly high correlations between the eyes and hand for MT and RST, respectively, and show the hand times exceeded those for the eyes. Notice that the higher correlations between the eyes and hand for MT and RST also exceeded those for RT.

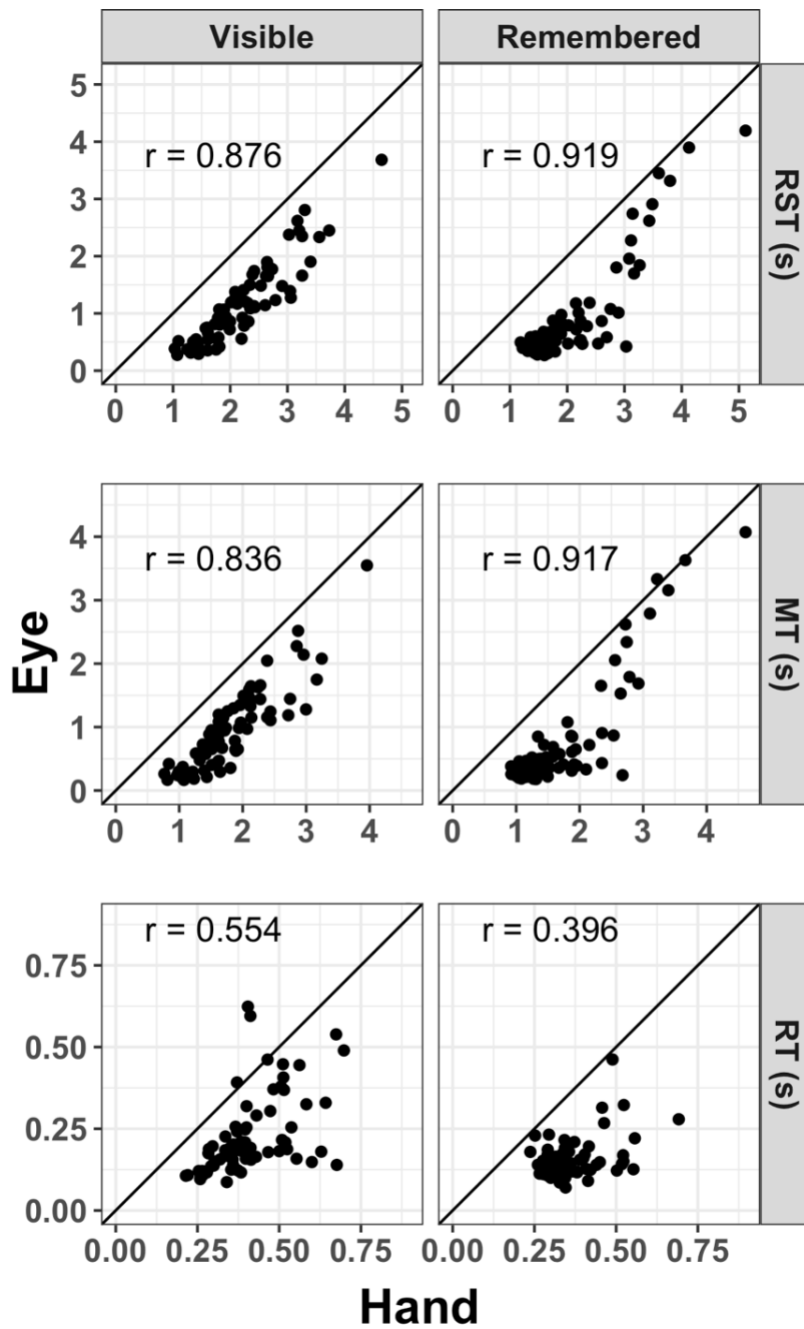


Figure 5.16. Correlation between Hand and Eye temporal variables.

Each dot represents the median values for the response time (RST-upper panels), movement time (MT-middle panels), and reaction time (RT-lower panels) of the eyes plotted

against the corresponding values for the hand of each subject in Visible (left panels) and Remembered (right panels) target conditions for each workspace. Diagonal lines represent lines of unity, thus equal values between the eyes and hand.

Discussion

The purpose of this research study was to assess whether the use of visual feedback of endpoint (allocentric cues) and movement trajectory (egocentric cues) will help participants successfully adapt to visuomotor rotations. We further assessed the effect of visual feedback on eye movements/gaze direction used and accounted for different contexts of workspace locations. We discuss the impact of visual feedback on visuomotor adaptation independent of workspace prior to accounting for workspace. This is followed by discussion on different temporal adaptive patterns of eye-hand coordination. We conclude this section with discussion on potential control strategies that account for our findings.

Visual feedback effects on visuomotor adaptation

We examined the effect of visual feedback on visuomotor adaptation. The contributions of gaze direction for Remembered and Visible target groups revealed differences in pathlength such that individuals in the Remembered target group underestimated pathlength, moving a longer distance than people in the Visible target group. This finding supported our first hypothesis for less spatial precision when targets are remembered and aligns with results from others in which reaches made to Remembered targets often led to overreaches associated with underestimations of endpoint location (Admiraal et al., 2003). The longer distance in the Remembered target group also accompanied a faster eye reaction time than the Visible target

group. A faster reaction time offers participants the opportunity to direct their gaze on the remembered target location quickly and before decay of spatial location, known to increase with time (Hesse & Franz, 2010; Lemay & Stelmach, 2005), could occur. The shorter reaction time for the Remembered target group left less time for planning movement (Dean, Marti, Tsui, Rinzel, & Pesaran, 2011) compared to the Visible target group, which likely contributed to the longer pathlength production.

After training, participants in both groups made several alterations in performances. They generated a significant reduction in initial direction error and pathlength which allowed them to improve their precision of movement, similar to previous studies (Balitsky Thompson & Henriques, 2010; Lei et al., 2013). Movement was also smoother and faster, and reactions were faster after training (see Figure 5.14 & 5.15). All participants significantly improved on both spatial and temporal variables after training on the visuomotor adaptation task. Despite the shorter RT and greater pathlength used by the Remembered target group, removing the endpoint target did not alter the course of adaptation, as expected.

After-effect results revealed that the applied visual rotational offset affected the spatial accuracy of the task, similar to others, in which greater initial direction error and pathlength existed immediately after rotation was removed (Balitsky Thompson & Henriques, 2010; Rentsch & Rand, 2014). As the spatial precision increased, thus decline, the movement got smoother and faster. Smoother and faster movements were also revealed in a similar task indicative of greater experience of task performance (Contreras-Vidal, Bo, Boudreau, & Clark, 2005). Interestingly, training a visuomotor adaptation task with remembered targets improved reaction times of the eyes and hand and response time of the eyes compared to performances with visible targets after

the rotation was removed. Thus, training with remembered targets would provide benefits for motor tasks where speed is favored.

Adaptive changes in eye and hand movements across workspaces

We also investigated how the type of visual feedback differentially affected the acquisition and transfer of visuomotor adaptation across workspace locations following training in the central workspace. There were workspace-related differences for pathlength, movement speed, movement time, and response times of the eyes and hand during task performance. Visuomotor adaptation task performance in the contralateral workspace appeared more challenging, as participants produced a longer pathlength, lower speeds, and longer movement and response times for the eyes and hand compared the central workspace, where training took place. Pathlength, movement speed, eye movement time, as well as eye and hand response times in the contralateral workspace also differed from the ipsilateral workspace in a similar manner. These findings were in line with previous studies that have reported ipsilateral advantages of motor task performance over the contralateral workspace without a visual rotational offset due to possible biomechanical constraints (Carey, Hargreaves, & Goodale, 1996; Carey & Otto-de Haart, 2001; Fisk & Goodale, 1985). Biomechanical constraints may also explain the shorter pathlength for ipsilateral compared to central workspace when people are presented with visual rotational offset.

Adaptation also differed across workspaces. For instance, hand reaction time in the central and contralateral workspaces significantly improved after training. Review of the data reveal similar reaction times for the hand across the three workspaces after training (Figure 5.8) to suggest a potential hand reaction time advantage in the ipsilateral workspace initially. Thus the

biomechanical advantage described previously (Carey et al., 1996; Carey & Otto-de Haart, 2001; Fisk & Goodale, 1985) may also apply to hand reaction time. Eye movement time and response time improved significantly post-training across workspaces with the largest effects observed in the contralateral workspace, where initial performances of movement parameters were poorest (see Figures 5.9 and 5.11), thus would have the greatest room for improvement (Barton et al., 2014).

We also observed increased movement speed across workspace locations for the Remembered target group but not for the Visible target group, in which movement speed was significantly greater post-training in the contralateral workspace. The greater increase in movement speed for remembered target could be due to the faster performance with training (Aiken, Pan, & Van Gemmert, 2017; Pan & van Gemmert, 2013a). The after-effect results provide greater insight into these possibilities.

The ensuing after-effects of visuomotor adaptation was differentially affected by workspace location. When rotational bias was removed post training, movement time reduced only in central and contralateral workspaces, while initial direction error and pathlength increased in central and ipsilateral workspaces. These after-effects indicated the rotational bias affected directional error and pathlength in the central and ipsilateral workspaces which is required for participants to update their internal control models (Larssen, Ong, & Hodges, 2012; Lim, Larssen, & Hodges, 2014; Ong & Hodges, 2010) and experience implicit adaptation (Gastrock, Modchalingam, T Hart, & Henriques, 2020). These data provide clear evidence to support results of others that show adaptation of direction and excursion, thus spatial information, in the central workspace can generalize to the ipsilateral workspace (Lei et al., 2013). The accompaniment of decreases or no

changes in movement time for central and ipsilateral workspaces, respectively, with increases in pathlength and initial direction error suggest additional training benefits of adaptation that transferred to the ipsilateral workspace.

Differences in adaptive patterns in eye and hand movements (pen drawings) for Visible and Remembered targets.

In this study we examined the gaze strategies participants used when visual feedback of the endpoint was and was not removed shortly after it was shown. Shorter reaction time for the eyes compared to the hand can occur because of mass differences, in which the arm requires a greater force to initiate movement than the eyes (Gribble et al., 2002) and/or coordination differences, in which the eyes often lead the hand to anchor gaze at the endpoint location in order to provide visual feedback for terminal hand placement (Rand & Rentsch, 2015, 2016, 2017; Rentsch & Rand, 2014). The greater correlation between the reaction time of the hand and eyes for Visible target group compared to Remembered target group likely corresponded to the need for the participants after target removal to direct their gaze at the remembered target prior to decay and support our hypothesis that gaze patterns would differ between types of visual feedback. Closer review of the gaze video recordings revealed that when the target was remembered, participants often made saccades toward the target area then hand movement followed, whereas in the when the target was visible participants often revealed multiple saccades toward the target area and back to the hand movement during its movement. These data show evidence for varied planning control for the eyes and hand like those that occur for goal-directed reaches to actual and remembered target locations (Flanagan, Terao, & Johansson, 2008).

Eye movements and Spatial attention

Eye movements allow for projection of light from an object of interest onto the fovea (Hunt, Reuther, Hilchey, & Klein, 2019) to posit that eye movements offer insight into visual attention (Clark, 1999; Hoffman & Subramaniam, 1995; Klein, Kingstone, & Pontefract, 1992; Kustov & Robinson, 1996). Hoffman and Subramaniam (1995) reported that visuospatial attention was a crucial mechanism for saccade generation. Behavioral evidence indicates before the onset of saccade, attention is directed toward the movement endpoint, and this improves perceptual discrimination at the target location (Baldauf & Deubel, 2008; Deubel & Schneider, 1996, 2003; Gersch, Kowler, & Doshier, 2004; Khan, Song, & McPeck, 2011). We showed that visual feedback is not required for visuomotor attention and subsequent saccade generation (Hopp and Fuchs (2004) for a visuomotor adaptation task.

In our current experiment, we used an adaptation paradigm to separate visual feedback and motor goals which might share attentional resources equally (Song & Bedard, 2013) as they do for goal-directed reaching (Khan et al. 2011). Visual attention at the early stages of a visuomotor adaptation task, which decrease in the less challenging conditions (60° applied rotation), are maintained in difficult conditions (120° applied rotation) (Reuter, Bednark, & Cunnington, 2015) suggesting that the difficulty of the task may modulate the relationship between attention and eye movements and potentially movements of the hand. Performances using the visual rotational bias in the contralateral workspace seemed the most challenging, as these performances required longer response times of the eyes and hand than in the other workspaces, and likely required greater attention to support this possibility.

Conclusions

Our study provided evidence that training in a visuomotor adaptation task with remembered target locations improve reaction time for unrotated visible targets regardless of workspace despite a decrease in reaching precision during adaptation. We also found that use of different gaze strategies are not relevant to visuomotor adaptation and visuomotor adaptation only transferred from the central to the ipsilateral workspace. We reasoned that biomechanical factors associated with performances in the contralateral workspace may be too challenging for the given training protocol.

CHAPTER 6. CONCLUSIONS

Through these experiments we aimed to gain knowledge about mechanisms contributing to the control of visuomotor adaptation in different workspace locations. We assessed visuomotor adaptation transfers across limbs in different workspace locations. Findings were used to assess whether the dynamic dominance model (Sainburg & Wang, 2002) is applicable to different workspace locations. We included another study to extend our knowledge of the mechanisms contributing to visuomotor adaptation by providing a neurophysiological perspective to support our understanding of adaptation in different workspaces. We further examined gaze strategies during adaptation and the effect of visual feedback manipulation.

Key results

In the first experiment (chapter 3), we observed the adaptation of movement parameters such as movement time, resultant velocity, and normalized jerk across all groups in all workspace locations. Workspace and hand differentially affected movement trajectory length. After-effects indicated pathlength was affected by the rotation and movement got faster and smoother. The group that practiced the task with their left hand showed larger after-effects for pathlength than those that practiced with their right hand. This could likely be due to the creation of a new internal model for the left hand whereas the right hand may have a pre-existing internal model which may require a longer time to switch (Wada et al., 2003). Visuomotor adaptation of pathlength transferred from the left to the right hand despite no after-effects observed. After-effects were observed for movement time and resultant velocity. In summary, the transfer of movement time and normalized jerk were persistent in the contralateral workspace. The results failed to support the dynamic dominance model (Sainburg & Wang, 2002; Wang & Sainburg,

2006) in the ipsilateral and contralateral workspaces due to the symmetric nature of transfer of pathlength. In the second experiment (chapter 4), participants adapted concurrently to the visuomotor rotation across all workspaces. Corresponding neural measures indicated workspace related changes, with the biggest differences between contralateral and ipsilateral workspaces consistent with the observed behavioral results. The observed neurophysiological patterns were mainly in the right central and parietal areas – brain areas involved in spatial processing (Capotosto et al., 2012; Malhotra et al., 2009; Szczepanski et al., 2010). We employed different movement parameters to bring to light mechanisms of visuomotor adaptation. The final experiment (chapter 5) investigated how the visual feedback manipulation affected visuomotor adaptation and effects of workspace location, considering gaze strategies. We showed motor plan generalized across workspace regardless of visual feedback manipulation (i.e., from the central to the ipsilateral and contralateral workspaces) with after-effects of directional information observed in the central and ipsilateral workspaces. Gaze strategies differed between the two groups (Visible vs Remembered target). Gaze may not directly relate to visuomotor adaptation but rather serve as a predictor of spatial attention. Training visuomotor adaptation with Remembered targets improves reaction time when the rotational bias is removed for Visible targets. The current dissertation adds to a list of visuomotor adaptation studies (e.g., Capotosto et al., 2012; Fernandez-Ruiz & Diaz, 1999; Heuer & Hegele, 2008; Krakauer, 2009; Pan & van Gemmert, 2013; Rand & Rentsch, 2016, 2017; Szczepanski et al., 2010; Wang, 2008; Wang & Sainburg, 2004, 2005, 2006) that increase our understanding of mechanisms responsible for adapting to a visuomotor rotation under different contexts.

Comparison across studies

In three experiments, we provided different mechanisms for visuomotor adaptation and mechanism of adaptation in different workspace location, with support from both a behavioral and a neurophysiological perspective to add to our understanding of movement control mechanisms. Findings from study 1 provided the foundation for patterns of adaptation in the different workspaces being studied and its generalization across hands by examining the consistency of the dynamic dominance model, which describes the asymmetric transfer of movement transfer across limbs (Sainburg, 2002). We extended previous experiments (Pan & van Gemmert, 2013a, 2013b; Sainburg & Wang, 2002) using a similar experimental paradigm by adding two more workspace locations. We showed that adaptation differed across workspace and hand, and this was parameter specific similar to findings by Pan and van Gemmert (2013a). The second experiment added neurophysiological measures, i.e., brain oscillatory measures, to understand workspace-related changes during visuomotor adaptation. The topographical plot showed significant changes in the right hemisphere, especially alpha changes in the right occipital regions consistent with behavioral patterns across workspaces. Participants adapted to the rotational bias in all three workspaces similar to previous studies (Heuer & Hegele, 2011; Krakauer et al., 2000; Lei et al., 2013) despite different workspace locations requiring different levels of visuospatial attention. The third study explores gaze strategies and the generalization of visuomotor adaptation across workspace following the training in the central workspace. We also observed different gaze strategies for different visual feedback. Finally, gaze strategies are not relevant to visuomotor adaptation as shown by Gouirand et al, (2019).

Summary

This project aimed to add to existing knowledge of the mechanisms contributing to visuomotor adaptation in different workspace locations. We studied visuomotor adaptation from both behavioral and physiological perspective. In the first experiment, we observed workspace location and hand differentially affected adaptation of movement trajectory length. In the second experiment, participants adapted to the visuomotor rotation across all workspaces with largest difference in neural activities observed between contralateral and ipsilateral workspaces in the right hemisphere. The final experiment investigated how manipulation of both visual feedback and workspace location affected visuomotor adaptation while considering gaze strategies under different contexts. We showed the motor plan for adaptation transferred to different workspace locations following training in the central workspace location. Also, gaze strategies were different under different visual feedback manipulation but was not relevant for adaptation. Remembered targets during rotational adaptation improves reaction time for unrotated Visible trials. Everything considered, our physical workspace, hand dominance but neither visual feedback type nor gaze strategies play crucial roles during visuomotor adaption. Also, the right parietal regions may provide additional insights into the observed workspace-related differences during visuomotor adaption.

Future directions

Our study also explored different movement parameters to bring to light mechanisms for visuomotor adaptation and changes the motor system undergoes when performing the task in different workspaces. While different performance parameters were explored, we did not study

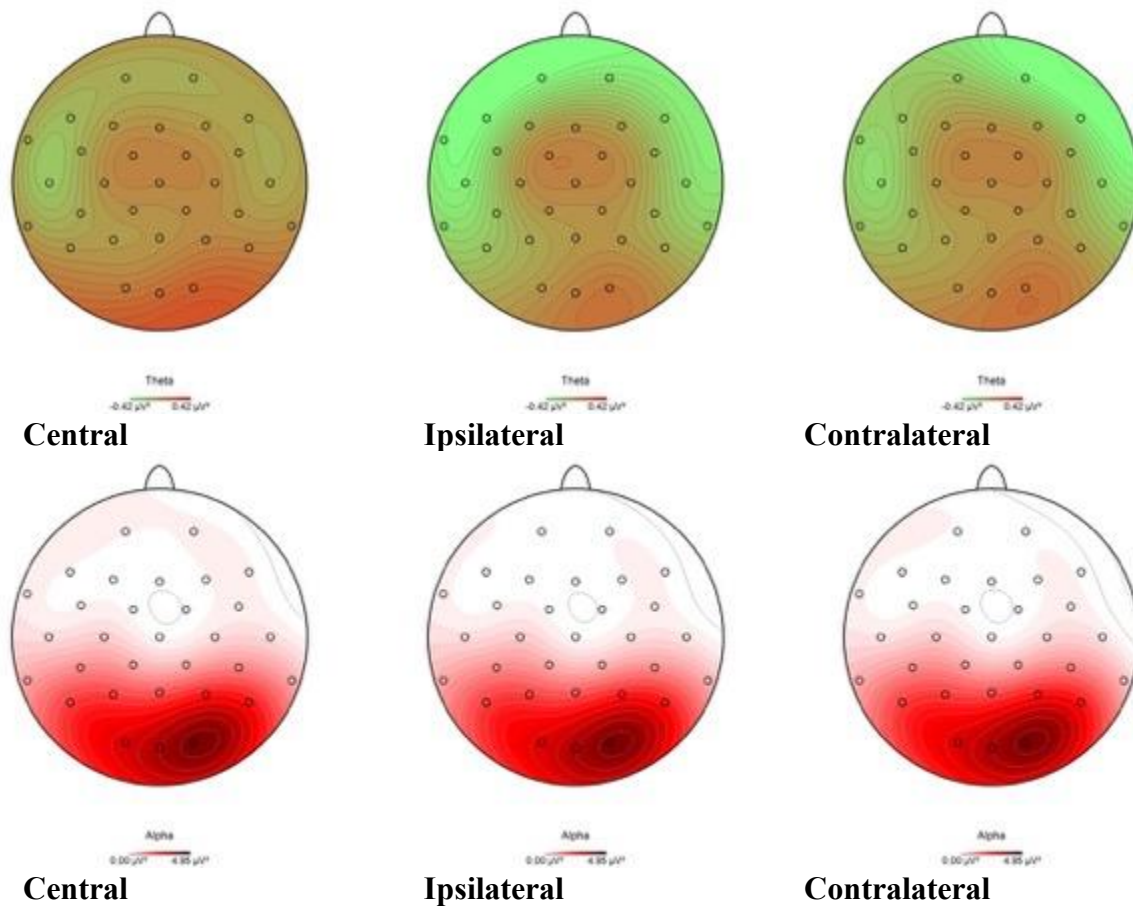
learning effects in the workspaces. Future studies should consider examining what features of movements are learnt in the different workspaces.

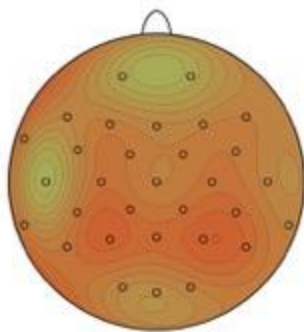
In the second experiment, we provided neurophysiological evidence for concurrent adaptation in the three workspaces, we posit differences in visuospatial processing evident as workspace related differences in cortical activity in the right parietal, central and occipital regions. Our current study used a 32-electrode EEG system, making it challenging to perform source localization analysis for specific brain areas. Future studies should consider an EEG system with more channels to perform source localization for specific brain regions. Furthermore, we did not investigate event-related EEG activity but rather an overall cortical activity for each workspace however, our behavioral analysis focused on performance differences between the first and last blocks. We analyzed overall EEG activity but not event-related. Event-related information could provide us with a better understanding of the functional role of the brain areas involved in processing workspace-related differences during visuomotor adaptation. Future studies should consider the use of an EEG system with more electrodes for task-related localization of cortical activities, furthermore event-related activity will provide more specific insight into the observed workspace changes. In the final experiment, we investigated the generalization of a visuomotor adaptation, taking into consideration how visual feedback impacts adaptation in different workspaces. We also investigated differences in gaze strategies and its impact on adaptation and its generalization following training. We did not perform point of gaze analysis in this study, this would have strengthened the argument of visuospatial attention in the generalization of adaptation.

APPENDIX A. TOPOGRAPHICAL MAPS

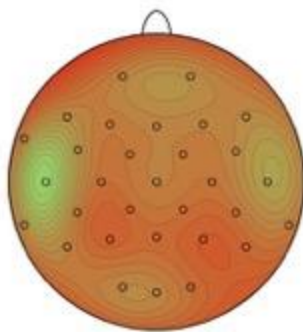
Alpha Waves results

EEG band mapping indicating activity change during visuomotor rotation performance compared to resting activity (i.e., Pre-Task performance per workspace condition). Illustrated are the Theta (4–7Hz) (upper row), Alpha (8–12 Hz) (middle row) and Beta (13–30 Hz) (lower row) band activities in the central workspace (left), ipsilateral (middle) and contralateral (right) workspaces.

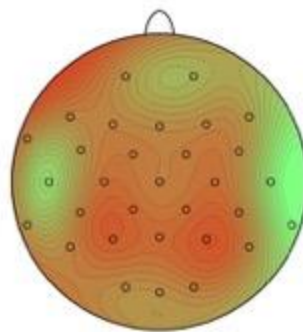




Central



Ipsilateral



Contralateral

APPENDIX B. DETAIL RESULTS FOR STUDY 3

IDE - Adaptation

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 6.846$, $p < .05$

Test: post-test - pre-test = -5.23° , $F_{(1,22)} = 10.909$, $p < 0.05$; $\eta^2 = 0.33$

Group: VIS - REM = 1.41° , $F_{(1,22)} = 0.33$, $p > 0.05$; $\eta^2 = 0.02$

Workspace: $F_{(1.57, 34.42)} = 17.902$, $p < 0.05$; $\eta^2 = 0.45$

Post-hoc tests

CTL – CEN = 7.86 , $p < 0.05$

CTL – IPS = 10.52 , $p < 0.05$

CEN – IPS = 2.66 , $p > 0.05$

IDE – After-effects

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 0.62$, $p > .05$

Mauchly's Test of Sphericity - Workspace x Test: $\chi^2(2) = 0.62$, $p > .05$

Test: post-test - pre-test = 4.53° , $F_{(1,22)} = 4.92$, $p < 0.05$; $\eta^2 = 0.18$

Group: VIS-REM = 2.55° , $F_{(1,22)} = 1.81$, $p > 0.05$; $\eta^2 = 0.08$

Workspace: $F_{(2,44)} = 1.50$, $p > 0.05$; $\eta^2 = 0.06$

Workspace x Test: $F_{(2,44)} = 8.62$, $p < 0.05$; $\eta^2 = 0.28$

Post-hoc tests

CEN: post-test - pre-test = 7.96° , $p < 0.05$; $\eta^2 = 0.24$

IPS: post-test - pre-test = 12.52° , $p < 0.05$; $\eta^2 = 0.38$

CTL: post-test - pre-test = -6.90° , $p > 0.05$; $\eta^2 = 0.12$

PL - Adaptation

Mauchly's Test of Sphericity – Workspace: $\chi^2(2) = 1.686$, $p > .05$

Test: post-test - pre-test = -1.31cm, $F_{(1,22)} = 55.471$, $p < 0.05$; $\eta^2 = 0.72$

Group: VIS – REM = -0.73cm, $F_{(1,22)} = 5.77$, $p < 0.05$; $\eta^2 = 0.21$

Workspace: $F_{(2, 44)} = 27.96$, $p < 0.05$; $\eta^2 = 0.56$

Post-hoc tests

CTL – IPS = 1.31cm, $p < 0.05$

CTL – CEN = 0.78 cm, $p < 0.05$

CEN – IPS = 0.53cm, $p < 0.05$

PL – After-effects

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 7.07$, $p < .05$

Mauchly's Test of Sphericity - Workspace x Test: $\chi^2(2) = 5.86$, $p > .05$

Test: post-test - pre-test = 0.72 cm, $F_{(1,22)} = 12.34$, $p < 0.05$; $\eta^2 = 0.36$

Group: VIS-REM = -0.08 cm, $F_{(1,22)} = 0.26$, $p > 0.05$; $\eta^2 = 0.01$

Workspace: $F_{(1.56, 34.22)} = 4.32$, $p > 0.05$; $\eta^2 = 0.16$

Workspace and Test: ($F_{(1.60, 35.10)} = 15.78$, $p < 0.05$; $\eta^2 = 0.42$)

Post-hoc tests

CEN: post-test - pre-test = 0.58 cm, $p < 0.05$; $\eta^2 = 0.22$

IPS: post-test - pre-test = 1.38 cm, $p < 0.05$; $\eta^2 = 0.49$

CTL: post-test - pre-test = 0.22 cm, $p > 0.05$; $\eta^2 = 0.06$

MT - Adaptation

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 4.59, p > .05$

Test: post-test - pre-test = -675.38 ms, $F_{(1,22)} = 58.30, p < 0.05; \eta^2 = 0.73$

Group: VIS-REM = 178.30 ms, $F_{(1,22)} = 0.42, p > 0.05; \eta^2 = 0.02$

Workspace: $F_{(2, 44)} = 12.62, p < 0.05; \eta^2 = 0.36$

Post-hoc tests

CTL – IPS = 301.30 ms, $p < 0.05$

CTL – CEN = 186.82 ms, $p < 0.05$

CEN – IPS = 114.48 ms, $p > 0.05$

MT – After-effect

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 4.53, p > .05$

Mauchly's Test of Sphericity - Workspace x Test: $\chi^2(2) = 0.88, p > .05$

Test: post-test - pre-test = -248.96 ms, $F_{(1,22)} = 6.31, p < 0.05; \eta^2 = 0.22$

Group: VIS-REM = 245.56 ms, $F_{(1,22)} = 0.97, p > 0.05; \eta^2 = 0.04$

Workspace: $F_{(2, 44)} = 4.73, p < 0.05; \eta^2 = 0.18$

Post-hoc tests

CTL – CEN = 132.03 ms, $p < 0.05$

CEN – IPS = -175.47 ms, $p < 0.05$

CTL – IPS = - 43.44 ms, $p > 0.05$

Workspace and Test: $F_{(1,22)} = 4.34, p < 0.05; \eta^2 = 0.17$

Post-hoc tests

CEN: post-test - pre-test = -222.08 ms, $p < 0.05$; $\eta^2 = 0.19$

IPS: post-test - pre-test = -93.23 ms, $p > 0.05$; $\eta^2 = 0.02$

CTL: post-test - pre-test = -431.56 ms, $p < 0.05$; $\eta^2 = 0.33$

RV - Adaptation

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 5.92$, $p > .05$

Test: post-test - pre-test = 2.12 cm/s, $F_{(1,22)} = 25.62$, $p < 0.05$; $\eta^2 = 0.54$

Group: VIS-REM = -1.70 cm/s, $F_{(1,22)} = 1.39$, $p > 0.05$; $\eta^2 = 0.06$

Workspace: $F_{(2,44)} = 1.97$, $p > 0.05$; $\eta^2 = 0.08$

Group x Workspace x Test: $F_{(1,22)} = 4.58$, $p < 0.05$; $\eta^2 = 0.17$

Post-hoc tests

VIS – CEN: post-test - pre-test = 1.13 cm/s, $p > 0.05$; $\eta^2 = 0.16$

VIS – IPS: post-test - pre-test = 1.48 cm/s, $p > 0.05$; $\eta^2 = 0.14$

VIS – CTL: post-test - pre-test = 1.79 cm/s, $p < 0.05$; $\eta^2 = 0.32$

REM – CEN: post-test - pre-test = 2.63 cm/s, $p < 0.05$; $\eta^2 = 0.50$

REM – IPS: post-test - pre-test = 3.62 cm/s, $p < 0.05$; $\eta^2 = 0.49$

REM – CTL: post-test - pre-test = 2.04 cm/s, $p < 0.05$; $\eta^2 = 0.38$

RV – After-effects

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 2.12$, $p > .05$

Test: post-test - pre-test = 1.72 cm/s, $F_{(1,22)} = 19.63$, $p < 0.05$; $\eta^2 = 0.47$

Group: VIS-REM = -1.35 cm/s, $F_{(1,22)} = 1.30$, $p > 0.05$; $\eta^2 = 0.06$

Workspace: $F_{(2,44)} = 3.56, p < 0.05; \eta^2 = 0.14$

Group x Test: $F_{(1,22)} = 10.74, p < 0.05; \eta^2 = 0.33$

Post-hoc tests

VIS: post-test - pre-test = 0.45 cm/s, $p > 0.05; \eta^2 = 0.03$

REM: post-test - pre-test = 3.00 cm/s, $p < 0.05; \eta^2 = 0.57$

NJ - Adaptation

Mauchly's Test of Sphericity: $\chi^2(2) = 0.64, p > .05$

Test: post-test - pre-test = -1172.79, $F_{(1,22)} = 11.65, p < 0.05; \eta^2 = 0.35$

Group: VIS-REM = -176.46, $F_{(1,22)} = 0.12, p > 0.05; \eta^2 = 0.01$

Workspace: $F_{(2,44)} = 3.53, p < 0.05, p = 0.038; \eta^2 = 0.14$

Post-hoc tests

CTL – CEN = 238.72, $p > 0.05$

CTR – IPS = 250.17, $p > 0.05$

CEN – IPS = -11.45, $p > 0.05$

NJ – After-effects

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 15.70, p < .05$

Test: post-test - pre-test = -756.67, $F_{(1,22)} = 12.66, p < 0.05; \eta^2 = 0.37$

Group: VIS-REM = -105.48, $F_{(1,22)} = 0.08, p > 0.05; \eta^2 = 0.003$

Workspace: $F_{(1,331,28.82)} = 1.16, p > 0.05; \eta^2 = 0.05$

Eye RT - Adaptation

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 5.46$, $p > .05$

Test: post-test - pre-test = -0.04s, $F_{(1,22)} = 4.34$, $p < 0.05$; $\eta^2 = 0.17$

Group: VIS-REM = 0.06 s, $F_{(1,22)} = 5.19$, $p < 0.05$; $\eta^2 = 0.19$

Workspace: $F_{(2,44)} = 0.35$, $p > 0.05$; $\eta^2 = 0.02$

Eye RT – After-effects

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 7.73$, $p > .05$

Test: post-test - pre-test = -0.01s, $F_{(1,22)} = 0.79$, $p > 0.05$; $\eta^2 = 0.04$

Group: VIS-REM = 0.03 s, $F_{(1,22)} = 0.96$, $p > 0.05$; $\eta^2 = 0.04$

Workspace: $F_{(2,44)} = 0.62$, $p > 0.05$; $\eta^2 = 0.03$

Group x Test: ($F_{(1,22)} = 2.05$, $p < 0.05$; $\eta^2 = 0.17$)

Post-hoc tests

VIS: post-test - pre-test = 0.02s, $p > 0.05$; $\eta^2 = 0.03$

REM: post-test - pre-test = -0.05s, $p < 0.05$; $\eta^2 = 0.17$

Hand RT - Adaptation

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = .601$, $p > .05$

Mauchly's Test of Sphericity – Workspace x Test: $\chi^2(2) = 1.36$, $p > .05$

Test: post-test - pre-test = -0.04s, $F_{(1,22)} = 5.11$, $p < 0.05$; $\eta^2 = 0.19$

Group: VIS-REM = 0.05s, $F_{(1,22)} = 2.58$, $p > 0.05$; $\eta^2 = 0.11$

Workspace: $F_{(2,44)} = 1.13$, $p > 0.05$; $\eta^2 = 0.05$

Workspace x Test: $F_{(2,44)} = 3.87, p < 0.05; \eta^2 = 0.15$

Post-hoc tests

CEN: post-test - pre-test = -0.06s, $p < 0.05; \eta^2 = 0.17$

IPS: post-test - pre-test = -0.01s, $p > 0.05; \eta^2 = 0.02$

CTL: post-test - pre-test = -0.06s $p < 0.05; \eta^2 = 0.27$

Hand RT – After-effects

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 4.83, p > .05$

Test: post-test - pre-test = 0.02s, $F_{(1,22)} = 1.60, p > 0.05; \eta^2 = 0.07$

Group: VIS-REM = 0.06s, $F_{(1,22)} = 2.97, p > 0.05; \eta^2 = 0.12$

Workspace: $F_{(1.55,41.73)} = 0.79, p > 0.05; \eta^2 = 0.03$

Group x Test: $F_{(1,22)} = 7.29, p < 0.05; \eta^2 = 0.25$

Post-hoc tests

VIS: post-test - pre-test = 0.03s, $p > 0.05; \eta^2 = 0.05$

REM: post-test - pre-test = -0.07s, $p < 0.05; \eta^2 = 0.26$

Eye MT: Adaptation

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 2.83, p > .05$

Mauchly's Test of Sphericity - Workspace x Test: $\chi^2(2) = 1.87, p > .05$

Test: post-test - pre-test = -0.44s, $F_{(1,22)} = 23.04, p < 0.05; \eta^2 = 0.51$

Group: VIS-REM = 0.21s, $F_{(1,22)} = 0.54, p > 0.05; \eta^2 = 0.02$

Workspace: $F_{(2,44)} = 14.45, p < 0.05; \eta^2 = 0.40$

Post-hoc tests

CTL – IPS = 0.33s, $P < 0.05$

CTL – CEN = 0.19s, $P > 0.05$

CEN – IPS = 0.14s, $P > 0.05$

Workspace and Test: ($F_{(2,44)} = 10.62$, $p < 0.05$; $\eta^2 = 0.33$)

Post-hoc tests

CEN: post-test - pre-test = -0.42s, $p < 0.05$; $\eta^2 = 0.38$

IPS: post-test - pre-test = -0.23s, $p < 0.05$; $\eta^2 = 0.32$

CTL: post-test - pre-test = -0.68s, $p < 0.05$; $\eta^2 = 0.56$

Eye MT: After-effects

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 5.33$, $p > .05$

Test: post-test - pre-test = -0.13s, $F_{(1,22)} = 1.34$, $p > 0.05$; $\eta^2 = 0.06$

Group: VIS-REM = 0.17s, $F_{(1,22)} = 0.86$, $p > 0.05$; $\eta^2 = 0.04$

Workspace: ($F_{(2,44)} = 0.84$, $p > 0.05$; $\eta^2 = 0.04$)

Hand MT - Adaptation

Mauchly's Test of Sphericity – Workspace: $\chi^2(2) = 0.95$, $p > .05$

Test: post-test - pre-test = -0.51s, $F_{(1,22)} = 37.72$, $p < 0.05$; $\eta^2 = 0.63$

Group: VIS-REM = 0.08s, $F_{(1,22)} = 0.13$, $p > 0.05$; $\eta^2 = 0.01$

Workspace: $F_{(2,44)} = 23.97$, $p < 0.05$; $\eta^2 = 0.53$

Post-hoc tests

CTL – IPS = 0.30s, $P < 0.05$

CTL – CEN = 0.16s, $P < 0.05$

CEN – IPS = 0.14s, $P < 0.05$

Hand MT – After-effects

Mauchly's Test of Sphericity – Workspace: $\chi^2(2) = 1.99$, $p > .05$

Test: post-test - pre-test = -0.09s, $F_{(1,22)} = 1.34$, $p > 0.05$; $\eta^2 = 0.06$

Group: VIS-REM = 0.08s, $F_{(1,22)} = 0.60$, $p > 0.05$; $\eta^2 = 0.03$

Workspace: $F_{(2,44)} = 4.54$, $p < 0.05$; $\eta^2 = 0.17$

Post-hoc tests

CTL – IPS = -0.07s, $P > 0.05$

CEN – IPS = - 0.12s, $P < 0.05$

CTL – CEN = 0.05s, $P > 0.05$

Eye RST - Adaptation

Mauchly's Test of Sphericity – Workspace: $\chi^2(2) = 2.28$, $p > .05$

Mauchly's Test of Sphericity – Workspace x Test: $\chi^2(2) = 1.36$, $p > .05$

Test: post-test - pre-test = -0.49s, $F_{(1,22)} = 24.80$, $p < 0.05$; $\eta^2 = 0.53$

Group: VIS-REM = 0.31s, $F_{(1,22)} = 1.03$, $p > 0.05$; $\eta^2 = 0.05$

Workspace: $F_{(2,44)} = 11.87$, $p < 0.05$; $\eta^2 = 0.35$

Post-hoc tests

CTL – IPS = 0.30s, $p < 0.05$

CTL – CEN = 0.18s, $p < 0.05$

CEN – IPS = 0.13s, $p > 0.05$

Workspace x Test: ($F_{(2,44)} = 8.54$, $p < 0.05$; $\eta^2 = 0.28$)

Post-hoc tests

CEN: post-test - pre-test = -0.48s, $p < 0.05$; $\eta^2 = 0.39$

IPS: post-test - pre-test = -0.28s $p < 0.05$; $\eta^2 = 0.37$

CTL: post-test - pre-test = -0.70s, $p < 0.05$; $\eta^2 = 0.56$

Eye RST – After-effects

Mauchly's Test of Sphericity - Workspace: $\chi^2(2) = 7.28$, $p < .05$

Test: post-test - pre-test = -0.14s, $F(1,22) = 1.68$, $p > 0.05$; $\eta^2 = 0.07$

Group: VIS-REM = 0.21s, $F(1,22) = 1.18$, $p > 0.05$; $\eta^2 = 0.05$

Workspace: $F_{(1.55,41.73)} = 1.42$, $p > 0.05$; $\eta^2 = 0.06$

Group and Test ($F_{(1,22)} = 4.42$, $p < 0.05$; $\eta^2 = 0.17$)

Post-hoc tests

VIS: post-test - pre-test = 0.08s, $p > 0.05$; $\eta^2 = 0.01$

REM: post-test - pre-test = -0.37s, $p < 0.05$; $\eta^2 = 0.21$

Hand RST - Adaptation

Mauchly's Test of Sphericity – Workspace: $\chi^2(2) = 1.09$, $p > .05$

Mauchly's Test of Sphericity – Workspace x Test: $\chi^2(2) = 3.88$, $p > .05$

Test: post-test - pre-test = -0.57s, $F_{(1,22)} = 11.43$, $p < 0.05$; $\eta^2 = 0.63$

Group: VIS-REM = 0.11s, $F_{(1,22)} = 0.51$, $p > 0.05$; $\eta^2 = 0.01$

Workspace: $F_{(2,44)} = 26.29$, $p < 0.05$; $\eta^2 = 0.54$

Post-hoc tests

CTL – IPS = 0.33s, $P < 0.05$

CTL – CEN = 0.19s, $P < 0.05$

CEN – IPS = 0.13s, $P > 0.05$

Workspace x Test: ($F_{(2,44)} = 4.39$, $p < 0.05$; $\eta^2 = 0.17$

Post-hoc tests

CEN: post-test - pre-test = -0.53s, $p < 0.05$; $\eta^2 = 0.56$

IPS: post-test - pre-test = -0.48s $p < 0.05$; $\eta^2 = 0.64$

CTL: post-test - pre-test = -0.69s, $p < 0.05$; $\eta^2 = 0.59$

Hand RST – After-effects

Mauchly's Test of Sphericity – Workspace: $\chi^2(2) = 1.73$, $p > .05$

Test: post-test - pre-test = -0.10s, $F_{(1,22)} = 1.26$, $p > 0.05$; $\eta^2 = 0.05$

Group: VIS-REM = 0.21s, $F_{(1,22)} = 1.20$, $p > 0.05$; $\eta^2 = 0.05$

Workspace: $F_{(2,44)} = 5.79$, $p < 0.05$; $\eta^2 = 0.21$

Post-hoc tests

CEN – IPS = - 0.15s, $P < 0.05$

CTL – CEN = 0.07s, $P > 0.05$

CTL – IPS = -0.09s, $P > 0.05$

APPENDIX C. IRB APPROVAL FORM



TO: Jan M Hondzinski
LSUAM | Col of HSE | Kinesiology
FROM: Alex Cohen
Chairman, Institutional Review Board
DATE: 23-Sep-2021
RE: IRBAM-21-0623
TITLE: Gaze behavior and endpoint information
effects on visuomotor adaptation

New Protocol/Amendment/Continuation: Amendment
Brief Amendment Description: Expanding the subject pool to those ages
18 to 40 years-old.
Review Type: Expedited Review
Risk Factor: Minimal
Review Date: 23-Sep-2021
Status: Approved
Approval Date: 23-Sep-2021
Approval Expiration Date: 22-Jun-2022
Re-review frequency: (annual unless otherwise stated)
Number of subjects approved: 100

By: Alex Cohen, Chairman

Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.

7. Notification of the IRB of a serious compliance failure.

8. SPECIAL NOTE: When emailing more than one recipient, make sure you use bcc.

** All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at <http://www.lsu.edu/research>*

Louisiana State University
131 David Boyd Hall
Baton Rouge, LA 70803

O 225-578-5833
F 225-578-5983
<http://www.lsu.edu/research>

APPENDIX D. CONSENT FORM

Title: Gaze behavior and endpoint information effects on visuomotor adaptation

Performance site: Kinesiology Labs in the Gym Armory (B1).

Contacts: The principal investigator is available for questions about the study

Monday - Friday, 9:30pm – 4:30pm

Jan M. Honzinski: jhondz1@lsu.edu

Reuben Addison: raddis3@lsu.edu

Arend W Van Gemmert: gemmert@lsu.edu

Purpose of study: The purpose of this study is to examine differences in gaze behavior when endpoint information is Remembered during the learning of a visuomotor task.

Participant Inclusion: Individuals from the Baton Rouge community, including LSU, who are from the ages of 18-40 years. Individuals who have normal or corrected-to-normal vision and/or hearing; Individuals, who are able to use a normal pen-grip (i.e., static/dynamic tripod/quadpod grasp); Individuals who do not have psychological, neurological, and/or other altered physical conditions affecting control of the upper dominant or non-dominant limb which conditions could be due to medications

Participant exclusion: Individuals outside of the Baton Rouge community. Participants outside of the age range 18- 40 years. Individuals who do not have normal or corrected-to-normal vision and/or hearing; Individuals, who are unable to use a normal pen-grip (i.e., static/dynamic tripod/quadpod grasp); Individuals who have psychological, neurological, and/or other altered physical conditions affecting control of the upper dominant or non-dominant limb which conditions could be due to medications

Number of Subjects: 100

Study procedure: You will be asked to read and sign the informed consent, to fill a handedness questionnaire, a short demographic questionnaire. Your response to the questionnaire is to obtain descriptive characteristics and ensure you meet the study's inclusion criteria. After filling out these forms, you will be seated comfortably in front of a screen and an opaque digitizer tablet (record movements made with a pen). You will be asked to put on a mobile eye-tracker that resembles large eyeglasses to track gaze during task performances.

During the task, you will be asked to use the pen to make drawing movements on the tablet while you see your movements on the screen. You will be asked to move the tip of the pen to a central circle and hold it in this circle till it disappears. The time it takes to get the tip of the pen in the central target is not important. When the central circle disappears, a new circle, called target, appears on the screen. You are asked to move the pen so that the cursor it controls moves as fast and as accurate as possible to the new target. The location of the target is unpredictable and in some cases will disappear once you begin to move. The time and accuracy of the drawing movement between the central circle and the new target is measured. The trial ends when you stopped in the target and subsequently lift the pen. You are required to stop in the target and leave

the pen in the target for a short time before you lift the pen. After lifting the pen, the next central circle will appear, and you repeat the process. The experiment will approximately take 2 hours of your time.

Benefits: No direct benefits will be offered to individuals outside the college community. Individuals belonging to the college community may receive extra credit for research participation in one of their classes. The information extracted from your performance will be beneficial to future study involving other populations.

Risks/Discomfort: No risks are foreseen, because participation in the present study would involve no more risk than that associated with drawing or writing during daily life. There is an inadvertent risk that information of your performance and the answers related to classification questionnaires are somehow made public. However, every effort will be made to maintain the confidentiality of the study records. Files will be kept in secure cabinets to which only university personnel have access.

Right to refuse: Participants may choose to withdraw or not participate in the study at any time without penalty or loss of any benefit that may be entitled.

Privacy: Results of the study may be published; however, no names or identifying information will be included. Identities will remain confidential unless disclosure is required by law. Data will remain confidential unless legally compelled.

Financial information: You will receive no financial compensation for participating and you have no financial obligations as result of participation.

Signatures: The study has been discussed with me, and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about subjects' rights or other concerns, I can contact Dr. Alex Cohen, Institutional review board, (225) 578-8692, irb@lsu.edu, www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the investigator's obligation to provide me with a signed copy of this consent if signed by me.

Participants signature _____

Date _____

Investigators signature _____

Date _____

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