EYE-HAND COORDINATION DURING ADAPTATION TO A NOVEL VISUOMOTOR ROTATION TASK AND UNDERLYING HEMODYNAMIC CORRELATES: AN EYE TRACKING AND *f*NIRS STUDY

AÇELYA YILDIZ

May 2017

EYE-HAND COORDINATION DURING ADAPTATION TO A NOVEL
VISUOMOTOR ROTATION TASK AND UNDERLYING HEMODYNAMIC
CORRELATES: AN EYE TRACKING AND *f*NIRS STUDY

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF SOCIAL
SCIENCES OF IZMIR UNIVERSITY OF ECONOMICS

BY

AÇELYA YILDIZ

May 2017

Approval of the Graduate School of Social Sciences
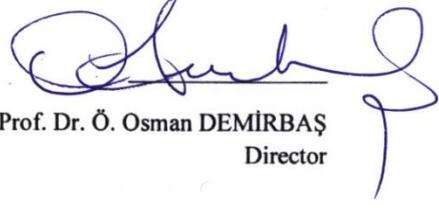
Assoc. Prof. Dr. Ö. Osman DEMİRBAŞ
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Seda DURAL
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Seda CAN
Supervisor

Examining Committee Members

Prof. Dr. Hakan ÇETİNKAYA

Assoc. Prof. Dr. Seda CAN

Assoc. Prof. Dr. Seda DURAL

ABSTRACT

EYE-HAND COORDINATION DURING ADAPTATION TO A NOVEL
VISUOMOTOR ROTATION TASK AND UNDERLYING HEMODYNAMIC
CORRELATES: AN EYE TRACKING AND FUNCTIONAL NEAR-INFRARED
SPECTROSCOPY (*f*NIRS) STUDY

Yıldız, Açelya

Master of Science in Experimental Psychology

Supervisor: Assoc. Prof. Seda Can

May 2017

The present study investigated the changes in eye-hand coordination during
adaptation to a novel visuomotor rotation task and the underlying neural correlates of
this process. Plus, the present study provided a comparative analysis regarding
traditional (linear) and circular trajectory manipulation. Changes related to reaction
time, eye-hand coordination and hemodynamic measurements were obtained for both
trajectory manipulations. Visual guidance was analyzed based on local components
determined as time interval between first eye fixation on target and target hit (eye-to-
shooting latency), time interval between first eye fixation on target and arrival of
cursor on target (eye-to-hand latency), time interval between arrival of cursor in
target area and target hit (hand-to-shooting latency), and time interval between first
eye fixation on a target and first eye fixation on next target (eye-to-eye latency).
Underlying neural correlates of adaptation to circular and linear conditions were
examined based on local oxy-Hb and deoxy-Hb concentration. Growth Curve
Analysis was used to analyze all measurements taken throughout the experiment.
Result of the analysis indicated that reaction time decreased as trials progressed with
circular condition resulted in longer reaction time. Eye-to-shooting and eye-to-eye
shooting latencies significantly decreased throughout trials, which were longer for
circular condition. Finally, circular condition resulted in higher oxy-Hb concentration
than linear condition while linear condition was paired with higher deoxy-Hb
concentration than circular condition, which indicated circular trajectory condition
required more oxygen consumption in the activated region. Increases in

hemodynamic activity were localized in DLPFC and VLPFC, consistent with previous research.

iv

ÖZET

YENİ BİR ROTASYON GÖREVİNE YÖNELİK GÖRSEL-MOTOR UYUM SÜREÇLERİNDE GÖZ-EL KOORDİNASYONUNUN VE BU SÜREÇLERİN HEMODİNAMİK TEMELLERİNİN İNCELENMESİ: BİR GÖZ TAKİP VE İŞLEVSEL YAKIN KIZILÖTESİ SPEKTROSKOPİ (*f*NIRS) ÇALIŞMASI

Yıldız, Açelya

Deneysel Psikoloji Yüksek Lisans Programı

Tez danışmanı: Doç. Dr. Seda Can

Mayıs 2017

Bu çalışmada yeni bir görsel-motor rotasyon görevine adaptasyon sürecinde göz-el koordinasyonundaki değişimler ve temelinde yatan sinirsel mekanizmalar incelenmiştir. Buna ek olarak, bu çalışmada geleneksel (doğrusal) rotasyon manipülasyonu ve dairesel rotasyon manipülasyonuna karşılaştırılmıştır. Tepki süresine, göz-el koordinasyonuna ve hemodinamik ölçümlere ilişkin değişmeler hem doğrusal hem de dairesel rotasyon görevleri için elde edilmiştir. Göz-el koordinasyonu yerel bileşenler aracılığı ile incelenmiştir: gözün hedefe ilk odaklanması ve hedef vurulması arasında geçen zaman; gözün hedefe ilk odaklanması ve elin hedefe varması arasında geçen zaman; elin hedefe varması arasında ve hedefin vurulması arasında geçen zaman ve gözün bir hedefe odaklanması ile bir sonraki hedefe odaklanması arasında geçen zaman. Doğrusal ve dairesel koşullara adaptasyon süreçlerinin temelinde yatan sinirsel mekanizmalar yerel oksijenlenmiş hemoglobin ve oksijenden arındırılmış hemoglobin konsantrasyonu temelinde incelenmiştir. Çalışma boyunca alınan bütün ölçümler Büyüme Eğrisi Analizi kullanılarak analiz edilmiştir. Analiz sonuçları tepki süresinin denemeler ilerledikçe azaldığını ve dairesel koşulun doğrusal koşula kıyasla daha uzun tepki süresine sebep olduğunu göstermiştir. Gözün hedefe ilk odaklanması ve hedefin vurulması arasında geçen süre ve gözün bir hedefe odaklanması ile bir sonraki hedefe odaklanması arasından geçen sürenin denemeler ilerledikçe azaldığı gözlenmiş ve bu sürelerin dairesel koşulda daha uzun olduğu gösterilmiştir. Son olarak, dairesel koşul doğrusal koşula göre daha yüksek oksijenlenmiş hemoglobin

konsantrasyonuna sebep olurken, doğrusal koşul dairesel koşula kıyasla daha yüksek oksijenden arındırılmış hemoglobin konsantrasyonu ile ilişkilenmiştir. Bu bulgu dairesel koşulun aktif olan bölgede doğrusal koşula göre daha yüksek oksijen tüketimine yol açtığını göstermiştir. Aktivite artışı gözlenen bölgeler literatür ile tutarlı olacak şekilde DLPFK ve VLPFK olmuştur.

Anahtar kelimeler: Görsel-motor uyum, göz-el koordinasyonu, rotasyon manipülasyonu, hemodinamik tepki, oksihemoglobin konsantrasyonu, deoksihemoglobin konsantrasyonu

To wings, leaves and paws.

ACKNOWLEDGEMENTS

making me understand that I was, in fact, never alone; and finally to my family for their ever standing support and motivation and their endless belief in me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

Introduction

The capability of demonstrating a motor behavior is undoubtedly related to quality of life for all species on the earth. The absence of this capability would result in a major constraint for performing many activities that are necessary for survival. From combing hair to pointing at an object in space, movement is generated with the involvement of muscles. Winter (2009) defines muscle as the "living" component of an organism's system. Even when solely standing up and during absence of any action, plenty of muscles are functioning to maintain this position. However, it is well-known that these muscles are not in charge of the movement and absence of movement by themselves. It is the central nervous system (CNS) which is in command of hundreds of muscles when a motor action is performed by the organism, sending directives through the peripheral nervous system (PNS) (SfN Brain Facts, 2006). And it is capable of generating and conveying information related to the required pattern for a specific movement aim.

The flow of information associated with the environmental cues and related motor action in the central nervous system and peripheral nervous system is carried out by specialized neurons (Lin et al., 1998). These specialized neurons contribute to transmission of information related to motor action. There are three types of neurons involved in this process: sensory neurons, interneurons and motor neurons (Blake et al., 2002). Sensory neurons are responsible for the detection of the stimuli through sensory receptors, which gather the environmental cues, and for transmitting the information to central nervous system. As the name suggests, interneurons provide the connection between sensory neurons and motor neurons by conveying the information obtained from sensory neurons to motor neurons. Finally, motor neurons relay the information to effectors which are muscles, glands or other related organs. At the end of this pathway the motor action is produced (Figure 1).

The question of how a motor action is produced by the body related to sensory cues can be explained by the transmission pathway described above, however; this is
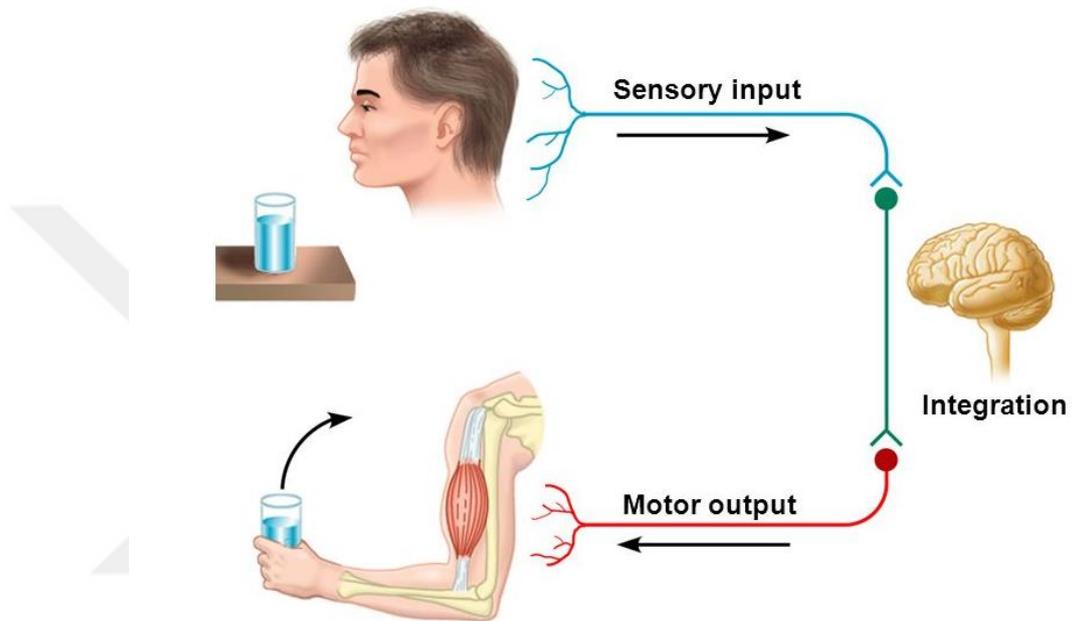
Figure 1. Sensory neurons receive the information from sensory receptor, and transmit this information with electrochemical signals to the brain and spinal cord. In the brain and spinal cord the integration of sensory information is carried out by interneurons. Finally motor neurons convey motor output signals to the effectors. Adapted from *Human Anatomy and Physiology*, *7e* by E.Marieb., K.Hoehn & M. Hutchinson. Copyright [2013] Pearson Education, Inc., publishing as Benjamin Cummings.

only a limited point of view, since it solely explains the production of the behavior in the presence of a stimulus. In daily life, it might not be possible to talk about constant stimulation related to a specific action. The foot performs circles with the pedal when riding a bike and the fingers tap on keyboard when typing. It would be unreasonable to form circles with feet while simply walking on the street or sitting at a cafe. Thus, the performed motor action is highly related to the type of the received sensory stimulus and that this stimulus might not be available on all occasions. Based on this information, it could be suggested that the organism either forgets how to perform the action or its association with the sensory stimulus since stimulation is not constant. As a matter of fact, this point of view is proven wrong with the capacity of organisms to preserve some or all of the information following this process, which is also referred to as motor learning.

Motor learning stands for the relatively permanent acquisition of a specific behavior as a product of the interaction between sensory and motor information gathered from the environment (Wolpert et al., 1995). Acquisition of a specific behavior, however, may not occur after a single encounter with the environment or a single performance of the learned behavior. An effortless performance of the desired action comes through practice, along with developing strategies related to that action (Gatti et al., 2013). Motor learning, therefore; can be defined as an outcome of the vigilant selection of sensory information provided by a proper context and exercising the desired behavior through enhancement and/or repetition. It can be understood that without sufficient experience with the context and the learned behavior, it is controversial to say that the acquired knowledge can be preserved permanently.

Willingham (1998) defines motor control as the usage of the acquired knowledge and increasing the frequency of this knowledge supported by planning and demonstration of behavior. It is possible to regard motor learning and motor control as united despite they stand for distinctive meanings. Since the factors that contribute to motor skills affect the acquisition of that skill, and the acquisition of that skill influences the factors that are responsible for the development and production of a motor skill. Along with this, the processes and conditions that facilitate motor learning and motor control consistently change and covertly interact. As two sides of a coin motor learning and motor control differentiate from each other

and can be investigated based on some details, however; they still remain as part of one coin (Edwards, 2011).

Following the acquisition of a specific motor skill, the desired behavior, preserving and performing that skill also contribute to motor learning. This process is referred to as motor skill learning. Motor skill learning, more inclusively, can be identified with a decrease in spatial and temporal error of a specific behavior through practice (Willingham, 1998). Motor skill learning is thought to occur in three phases with particular characteristics of their own; (1) Initial stage: unprofessional, extremely controlled slow motor responses that require frequent feedback attention, performance with numerous errors, lack of acquaintance with the sensory-motor map; (2) Intermediate stage: more precise movements, lessened reliance on frequent feedback, increase in speed, decrease in error, and grasp of the sensory-motor map; (3) Advance stage: professional movements, speed maximization, movement error on rare occasions and mastery of the sensory-motor map (Halsband and Lange, 2006; Wolpert et al., 1995). Therefore; in the early stages of learning, organisms try to determine the correct behavior and to do this, performance is heavily dependent upon sensory information. This phase is thought to be closely related with attention paid to sensory cues in the environment (Petersen et al., 1994). Following the initial phase, the correct movement is determined and at this point the interaction between sensory cues and motor action, more specifically; sensorimotor translation is crucial. The translation of sensory stimuli into motor output occurs with the aid of working memory which temporarily retains sensory cues (Deiber et al., 1997). Through the last phase the desired behavior becomes automatic and is performed effortlessly by the organism without the necessity for intense attention.

The statements above provide insight to how the assessment of motor skill acquisition can be carried out, as each stage has its own predictors related to precision of movement and reliance on feedback. What is known, almost obviously, is that when individuals are presented with an unfamiliar or modified motor action in an unfamiliar or altered context, mistakes will most likely occur during initial performance. Mastery of the sensory-motor map begins to take place after necessary amount of practice with the novel task and there will be reduction in the time participants spend to perform the required behavior. Indeed, some studies suggest that motor skill learning is generally measured through observations of reduced

reaction time, decrease in errors, precision in desired movement and alteration in movement synergy and kinematics (Shadmehr and Holcomb, 1997; Karni, 1996).

Motor skill learning is studied based on the experimental paradigms that are divided into two fields; first is motor sequence learning which measures the augmented acquisition of a motor skill into nearly professional behavior, and the second is motor adaptation which examines the ability of adapting to an environmental change (Seidler, 2010). When new sequences are learned, individuals turn separate behaviors into neat and synchronic behaviors (Ungerleider et al., 2002). Sequential learning can be exemplified with separate behaviors acting at once in harmony while playing soccer, golf etc. Thus, sequential learning means the regulation of unrelated and unregulated movements into synchronous sets of movements. Motor adaptation, in other words sensorimotor adaptation, is defined as the process of acquiring, maintaining and demonstrating a motor skill (Krakauer, 2006). When motor adaptation occurs, the individual is capable of acting in harmony with the environment and in addition to owning the potential to perform this, also uses this potential. Thus, motor adaptation is crucial for consolidation and demonstration of a motor skill. Both motor sequence learning and motor adaptation aim at explaining the process by which demonstration of a motor skill is performed effortlessly (Doyon et al., 1996). Even though these two can be taken into consideration as parts of a whole, Seidler (2010) stated that while tasks related to sequential learning or sensorimotor adaptation are performed, different regions of the brain are activated.

1.1. Theories of Motor Learning

Despite the acquisition of a motor skill can easily be defined with intervening and moderating factors, how it comes to have a representation in the brain is another issue. The faith for a neural representation arises from wondering how the behavior can be repeated over time and how the organism performs similar actions with small amount of trouble. Imagining that each and every single behavior related to different contexts has their own part in the neural system; it would be a huge waste of space, not to mention the difficulty of recalling and distinguishing a specific behavior. Kawato (1999) provides a detailed response for this question; that there is an internal model which can replicate the learned behavior including the input and output characteristics and it is preserved by a motor program which modulates the amount

of information that will be given to the organism about the desired behavior. This internal model can be thought as a neural mechanism which allows for generalization of the learned behavior to different types of apparatus and also multiple contexts. Plus, as it is capable of mimicking the input and output information, processing of sensory cues and necessary motor commands, it provides a template for more complex actions, including trajectory formation. Thus, internal model eliminates the need for a wide space of behavior representation and it might be possible to suggest that it frees the organisms from refraining to a limited repertoire of motor behaviors. Additionally, it allows the organism to generate movements similar to the previously learned behavior.

Some studies that are available in motor learning research domain are conducted to understand and define the relationship between motor skill learning and motor control. In these studies some theories are put forward. One of the earliest theories came from James (1950), related to chained schedules of behavior. Chained schedules of behavior is a component of Open-Loop Theory of motor learning, for which James states that motor program sends all of the required information for task completion in the beginning. In chained schedules of behavior there is a triggering factor for the beginning of a motor action and this factor comes from the environment. Once the action is triggered the chain will continue until the behavior is completed. The behavior or the chain of behavior remains uninterrupted by environmental factors or provided feedback. In this process, sensory information is what connects the chains to each other (Sulzer-Azaroff and Mayer, 1991). James mentions two types of chained schedules of behavior: heterogeneous and homogeneous chained schedules. The difference between these schedules is that while in heterogeneous schedule the sensory information between chains should be distinct from the previous triggering factor, in other words, a novel or more enhanced information is required; in homogeneous chained schedule there is no need for a change in the triggering factor among the chains of behavior. As it can be understood from statements made above, James fails to account for the effects of feedback on motor skill learning by classifying it as an uninterruptable process.

Closed-loop theory proposed by Adams (1971) suggests that the crucial factor in motor skill learning is not the flow of action, but rather how the sensory information is processed. The sensory information carried to central nervous system

activates a specific memory trace and generates a starting point for accurate performance of motor action which is the initial movement information. Memory trace is referred to as a modest motor program and it is involved in initiating direction of movement. This ability comes from knowledge of results (KR) and training. Thus, from the initial point, organisms need to receive KR to perform further action. Perceptual trace is responsible for positioning the limb on the right location during action. Perceptual trace gathers necessary information from the environment through visual, auditory and proprioceptive cues. Proprioceptive cues provide necessary information related to the position of the body and movement without the organism being consciously aware of this process (Lephart et al., 1997). Feedbacks obtained through and at the end of performance helps regeneration of the point in memory and this is utilized in testing the synchronization between perceptual trace and motor action. Closed-loop theory fails to account for the development of new motor programs and suggested that these programs are innate in the organism.

The schema theory developed by Schmidt (1975) was formulated to address the inadequacies of the theories mentioned above. According to the schema theory, a motor program includes some general rules related to motor action rather than a direct representation of the relationship between stored memory trace and desired motor action. These rules include the sequence of the action, the timing organization of the action and the strength required to perform the action, all of which refer to an unmodifiable representation or schema. In its most general form, this schema provides an appropriate representation for a general motor program, providing the brain with saving great portion from the memory load. This schema not only provides predetermined sets of rules for motor action, but also a capability for updating itself through parameters paving the way for acquiring new motor behaviors and performing related behaviors.

1.2. Acquisition of a Motor Skill and Influential Factors

When investigation related to motor skill acquisition is concerned, as well as comprehending the nature of this process and underlying mechanisms, understanding the influential factors is also crucial to achieve a decently prepared environment. This section of the study involves multiple strategies to study motor learning and some factors that might interfere with or have facilitative effects on skill acquisition.

Motor learning and motor control, at the base of everything, require acquisition of knowledge and without knowledge it is difficult to talk about either one of them. Acquisition of knowledge can occur in more than one form: implicit and explicit learning. Implicit learning refers to the acquisition of knowledge without applying conscious analytic strategies and the individual is completely unaware of this process while explicit learning occurs when individuals acquire knowledge with applying conscious analytic strategies in addition to utilizing problem-solving strategies (Berry and Dienes, 1993). Articulation of acquired skill and knowledge is highly improbable in implicit learning; however, in explicit learning it is possible to articulate since the knowledge is available at conscious level (Hayes and Broadbent, 1988).

Whether the learning will occur implicitly or explicitly can be manipulated by the researcher. If the aim is to provoke explicit learning, then the researcher can provide detailed explanation of every phase of the experiment and what the participant needs to perform at each particular step for successful movements. Implicit learning can be achieved by preserving the information related to successful movement and if a manipulation is employed during the experiment, participants are left unaware of this fact. Studies conducted to provide comparison related to implicit and explicit learning strategies commonly suggested that implicit learning was much more beneficial than explicit learning not in defining the nature of the task but in performance related to the task (Curran and Keele, 1993; Reber, 1989).

The acquisition of a motor skill is not only dependent on repetition and practice related to the desired behavior, but also on the timing of the practice. Two types of timing can be mentioned here: massed and spaced (Ebbinghaus, 1964). As the names suggest, massed schedules refer to continuous practice of the acquired motor action without any break and spaced schedule includes resting periods between trainings. According to Ebbinghaus, memorization of spaced sets of meaningless words took place much faster than memorization of massed sets of meaningless words. This suggests that inter-trial interval has crucial role to play in motor still learning as breaks in-between practices result in better performance.

Another issue related to timing is the length of inter-trial interval. A study conducted by Bock and his colleagues (2005) revealed that participants were much more efficient in detecting a brand-new change in visual environment after 5-40

seconds inter-trial interval than a 1 second inter-trial interval. Similarly, Francis (2005) demonstrated that participants were more successful in moving a robot-arm in a force-field when inter-trial interval was between 5-20 seconds rather than 0.5 seconds. Moreover, preservation of the acquired motor skill was proven to be stronger with longer inter-trial intervals (Smith et al., 2006; Kording et al., 2007). Thus, it can be inferred that when the resting period between practices is maintained short, then adequacy of performance might be poorer than the performance after training with longer resting periods between trials.

Self-controlled practice is also considered as an effective factor in motor skill learning. Self-controlled practice refers to the situation when participants are not provided with any help during performing the desired movement (Bund and Wiemeyer, 2004). Janelle and colleagues (1997) conducted a study to compare the permanency of acquisition after self-controlled practice and practice through assistance. The results of the study demonstrated that self-controlled practice produced more permanent acquisition related to the acquired knowledge compared to practice through assistance. Moreover, several studies suggested that self-controlled practice provided participants with the opportunity to get more involved during motor skill learning and therefore increased motivation (Meece, 1994; Ryan and Deci, 2000). Thus, providing participants with assistance during acquisition of a motor skill might have degrading effects on performance and absence of assistance might actually lead to better progress.

Frequency of feedback is another intervening source when skill acquisition is in concern. It might be considered that providing frequent feedback would have influences towards improvement in performance, however; Salmoni and colleagues (1984) suggested that when feedback is provided for each action, participants might rely on them solely, disregarding internal cues and failing to generate cognitive strategies. Disregarding internal cues and lack of strategies may eliminate the possibility of forming an internal model related to the acquired skill. Moreover, frequent feedback will result in high attention paid to correcting previous mistakes and focus on learning will be disrupted (Schmidt, 1991).

1.3. Visuomotor Adaptation

Visuomotor adaptation is the process in which a well-learned sensorimotor translation is modified based on changes in context or required behavior on neural maps used by the motor control system (Cunningham, 1989). Visuomotor adaptation, unlike new skill acquisition, does not necessitate learning new muscle activation patterns, but a new visuomotor mapping rule between the learned behavior and the requirements of the new context (Krakauer, 2009). Visuomotor mapping refers to the relationship between the hand's actual and visual locations. This mapping rule can be modified via devices or forces. Modification of a visuomotor map takes place through some processes like error encoding and updating visual cues to motor control system. The relationship between hand's actual and visual locations can be modified by applying visuomotor rotation. Visuomotor rotation is a screen-cursor modification providing a systematic directional bias in the hand and can be used to investigate the planning behind reaching direction (Krakauer et al., 2000). The rotation that is mentioned above is a trajectory or stimulus manipulation with a specific clockwise (CW) or counter-clockwise (CCW) degree. Adaptation to such a manipulation refers to the process of trial-by-trial error reduction as practice of behavior with the new rule increases. This process is also referred to as rotation learning.

Within the scope of visuomotor rotation, various types of CW or CCW manipulations can be applied. Manipulation related to the location of the target (Schaffert, 2014), to the visual feedback of movement performed by the unseen hand (Nourouzpour et al., 2015), or to the movement of the cursor (Krakauer et al, 2005) are stated among these various types of manipulation. Manipulation of the location of the target is achieved by locating the targets at different CW or CCW degrees around the cursor and participants are expected to move the cursor towards the targets and reach the targets, which are randomly presented at these locations. At occasions when the visual feedback of the hand's movement is manipulated, participants have no vision of their hand and the path created by the hand is displayed on a tablet with a CW or CCW rotated degree. Lastly, manipulation related to the movement of the cursor is achieved with applying a CW or CCW modification on the trajectory of the cursor. In this kind of manipulation participants are able to see their hands and

targets are fixed, however, while participants initiate movement towards the target the cursor moves in a rotated pattern.

As it was mentioned before, acquisition of a motor skill can occur in explicit and implicit forms. The process of adaptation to a visuomotor rotation is generally deemed as implicit (Kagerer et al., 1997, Frensch, 1998). Mazzoni and Krakauer (2006) revealed that when participants are informed of the characteristics of modification, they tend to perform more errors than the participants who were uninformed of the modification. This occurred since participants became indulged more with following the rule than with performing the desired action, thus they failed to produce a cognitive strategy. Without a cognitive strategy it is difficult to talk about rotation learning, let alone the formation of an internal model related to the learned movement. Thus, informing the participants related to the applied modification might result in an obstruction for the preservation of the acquired motor skill.

Buch and his colleagues (2003) defined the process of visuomotor adaptation as the mapping between the visual cues of the new environment and motor commands related to the output. Thus, visuomotor adaptation requires the involvement of a mechanism that is capable of transforming the visual position of the target to integrated motor behavior. Based on the information provided above related to internal models, it is not farfetched to suggest a crucial role for a motor program and a mapping rule during visuomotor adaptation. Visuomotor adaptation tasks have been used to make inferences about this transformation provided by the internal model (e.g. Kagerer et al., 1997; Klassen et al., 2005; Caithness et al., 2004).

The task used in this study was also a visuomotor rotation task since with its complexity; it requires transformation of the obtained sensory information to necessary motor (manual) outputs. The type of manipulation was determined as counter-clockwise rotation in the trajectory of the cursor. Two studies were conducted within the frame of this thesis utilizing the same task. However, specific aims and recruited sample for Study 1 and Study 2 were different. Therefore, rest of this section will be divided into two parts while providing information concerning the notion of the study and the related works in literature. Following these two parts; an overview of literature related to Study 1 and Study 2 will be presented together.

Lastly, final part of this section will include specific aims, research questions and hypotheses for Study 1 and Study 2.

1.4. Study 1

As it was mentioned before, motor actions can be acquired through practice and that contextual cues play a crucial part during this process. The role of manual movements in both acquisition and performance is substantial, since motor behavior is highly related to bodily movements. Yet, it is the visual guidance that generally provides crucial contribution to manual movement as without visual guidance, especially when a visuomotor adaptation task is in concern, it would be impossible to talk about the interaction between sensory and motor neurons, which can also be referred to as sensorimotor integration. Based on this statement, Study 1 will focus on the interaction between visual information and manual movement during visuomotor adaptation. This interaction which is made possible by the visual guidance is generally referred to eye-hand coordination.

1.4.1.   Eye-hand Coordination during Visuomotor Adaptation

Eye-hand coordination is suggested to provide noteworthy assistance, especially in planning and executing movement (Gaveau et al., 2008; Bowman et al., 2009). It involves contribution of many sensorimotor systems such as visual system, vestibular system, the eye, head and arm control systems and involvement of attention and memory (Crawford et al., 2004). In a target-hit task, it is the eye which fixates on the target and patiently awaits the arrival of hand to the target. Therefore, eyes not only guide the manual movement towards target, but also locate the target by fixating to it until successful manual response is performed. Johansson and his colleagues (2001) suggest that through this fixation, eyes allow for the brain to estimate the geometric relationship between the context and the current location of hand to perform the required behavior.

While performing daily activities, meaning activities that are previously learned, individuals do not constantly rely on visual information. When there is a bottle of water on the table, individuals do not fixate on the bottle top to turn it, rather most of the time they perform the movement without even looking at it. In an incident when their action results in an unexpected outcome, then they will tend to shift gaze towards the bottle top to understand the reason behind it and also maintain

the eyes there until the hand manages to open the bottle. Indeed, it is suggested that during daily life, eyes and manual movements are mostly unrelated (Steinman 2003; Fischer et al., 2003), and on the other hand, while motor learning occurs they seem to be coupled (Miall et al., 2001; Calton et al., 2002). The presentation of a rotation manipulation, therefore, will motivate the individuals to shift their gaze towards the source of the irregularity and to also fixate on the target point to guarantee that the required movement is completed by the hand.

Crawford and colleagues (2004) suggested that rather than a slow sensory feedback mechanism, eye-hand coordination uses the advantages of internal models to operate with motor system and the contextual cues rapidly. A comprehensive analysis related to eye-hand coordination during motor learning can be conducted during "early-phases" of learning as during "late-phases" the focus becomes the control of limb movement rather than relying on information provided by the foveal activity (Flanders et al., 1992). Flanders and colleagues also suggest that a reference frame transformation is at play during eye-hand coordination, which refers to a shift from gaze-centered frame to hand-centered frame. Therefore; guidance provided by foveal information is generally limited to initial struggle in an altered context or during performing unfamiliar task. This provides further support for the bottle of water example stated in the previous paragraph that visual guidance steps in only when there is an unexpected or unfamiliar change in the movement or the context.

Numerous studies pointed at the significance of visual feedback during rapid limb movements and found out that without visual feedback, the movement patterns were deteriorated (Keele and Posner, 1968; Meyer et al., 1988; Woodworth, 1899). Abrams and colleagues (1990) stated that two types of visual feedback are involved in guiding manual movement that are; retinal and extra-retinal. Retinal information is provided when the image of target is at the center of the foveal retina and the fixation is made on the target itself, and extra-retinal information is provided when image of target is not on foveal retina but it is still in the visual field. It was proven that extra-retinal information also plays a crucial part in guiding limb movement and in some situations solely extra-retinal information was sufficient in providing contextual information (Morgan, 1978; Hill, 1972).

An aimed limb movement is thought to occur in three phases: movement preparation, initial impulse and error correction (Meyer et al., 1990; Kerr, 1978). In

movement-preparation phase, which starts immediately after decision is made and sets of commands are sent from the motor program, both retinal and extra-retinal information are significant (Prablanc et al., 1979). The initial-impulse phase is when a primary movement is made towards the target and during this phase control is more dependent on the motor program which lowers the necessity of foveal guidance (Crossman and Goodeve, 1983). During the error-correction phase, defined as the process of the organism trying to cover the distance between limb position and movement goal, presence of retinal information is strongly necessitated (Wallace and Newell, 1983).

The studies conducted to examine eye-hand coordination during different types of tasks and contexts took various measurements regarding responses produced by the eyes. One of these measurements is the gaze behavior, which refers to the overall foveal movements and direction of foveal retina towards a specific stimulus (Bowman et al., 2009). Gaze behavior provides significant information related to the location of the eye, also referred to as eye orientation, such as gaze shifts towards the target or other non-target areas or stimuli. Another measurement is saccadic eye movements, which is the path created by the eye between two or more locations of interest (Gaveau et al., 2008). More inclusively, saccades provide the pathways or lines that foveal movements create when individuals shift their gaze from one point in the environment to another. Fixation and non-fixation are also among these measurements which respectively refer to the time when gaze is fixed on a target, which is also called as gaze anchoring, and when gaze is fixed on non-target areas (Von Hofsten, 1982). These measurements can be utilized to make comparisons between eyes and hands, to make inferences about temporal coupling between the two, and to conduct a comprehensive analysis on latency and accuracy of both foveal and manual actions.

Several studies investigated eye-hand coordination during a visuomotor rotation task to enlighten the relationship between visual information and manual movement (e.g. Abrams et al., 1990; Sailer et al., 2005; Rentsch and Rand, 2014). The study conducted by Abrams and colleagues (1990) monitored participants' gaze location when they were asked to adapt to a wrist rotation manipulations in a target-hit task and participants used a handle to perform the task. They conducted three separate experiments with the first two recruiting the same participants (four right-

handed undergraduate students) and third experiment including six right-handed undergraduate students who were different from the participants in the first two experiments. In the first experiment, participants were instructed to move their eyes in synchrony with their wrists. In the second experiment, participants were prevented from looking at the target and their performance was recorded again. In the third experiment, they allowed for visual guidance and plus, they were also allowed to make saccadic movements towards the target independently of their wrists. The rotation manipulations were clockwise when the handle was moved rightward and counter-clockwise when the handle was moved leftward. The manipulation resulted in the cursor to rotate 0.29° of visual angle, meaning that when the handle was located in 10° counter-clockwise on the screen, movements resulted in 2.9° rotations. In all of the experiments, participants performed during six fifty-minute session with repeating the same task. While in first experiment they observed a synchronous action of eye and hand movements, in the second experiment there was serious deterioration in the movements participants performed. The improvement in performance was again observed in third experiment where they were allowed to make saccadic shifts towards the target. This study proved the significance of visual guidance of the eyes in adapting to a visuomotor rotation task.

Sailer and colleagues (2005) investigated changes in gaze behavior when participants learned a complex visuomotor rotation task which necessitated usage of both hands. The sample of the study consisted of 10 participants, (4 females and 6 males, aged between 21-34 years), all of whom were right-handed. They provided participants with cylindrical handles that controlled the movement of the cursor on the screen. The task required participants to hit a total of 500 targets that were presented on the screen in two sessions. In the first session; a rule was applied on the cursor which caused the cursor to move left when participants used compression force and to move downward when participants performed torques with the handles and in the second session the opposite occurred, meaning that when participants used compression force the cursor moved downward and when they performed torques it moved to the left. Foveal data was obtained as gaze behavior from participants throughout the sessions and manual movements were also recorded. The analysis conducted on gaze behavior during task performance indicated that with adapting to this rule, participants shifted their gaze swiftly to the next target even when the

manual movement was incomplete. This was interpreted as an indicator of adaptation to a complex visuomotor rotation task as the necessity for visual guidance decreased.

Rentsch and Rand (2014) conducted the study to investigate the adaptive changes of eye-hand coordination during a visuomotor rotation task while they manipulated the visual feedback provided to participants. They sampled 30 participants (M_{age} = 24.0 with 15 males and 15 females), and all of them dominantly used their right hands. Feedbacks were either veridical (real) or rotated (unreal). The visual feedback was modified with three linear rotation angles (30°, 75°, and 150°) tested in three different groups. On the screen, there were four targets which were located at 45°, 135°, 225° and 315°. The measurements were taken from participants at three points: pre-test 1, post-test 1 and post-test 2 (Figure 2). The results of the study revealed that with practice the time it took participants to reach the target was decreased and while in 30 and 75 degrees of trajectory participants' gaze moved to an area between starting position and target to understand the manipulation, in 150 degrees the eyes were generally maintained around/on the screen cursor. Moreover, results suggested that role of visual guidance is to provide an exploratory point of view between manual movement and the cursor at the beginning and a predictive point of view, decreased guidance for hand on the present target but initial guidance on the next target, through the end. These studies mentioned above emphasize the crucial role of visual guidance during adaptation to a visuomotor rotation task since the unavailability of visual guidance was revealed to be a predictor of less successful performance. In addition to this, they also provide insight to the changes in eye-hand coordination during various phases of visuomotor learning through making inferences related to both foveal and manual movements. Moreover, the guidance provided by the eye was proven to be task-free, meaning that regardless of the type of the presented visuomotor rotation task, at least during initial phases, eyes supplied essential contribution.

1.5. Study 2

All movements that are performed by the body are initiated and monitored by the brain. Likewise, the brain is informed of every part of the body and their functions. Thus, it would not be possible to consider bodily actions and the brain separately, while there is a manual response produced by the body. The main intention regarding Study 2 is to understand the neural correlates of visuomotor

16
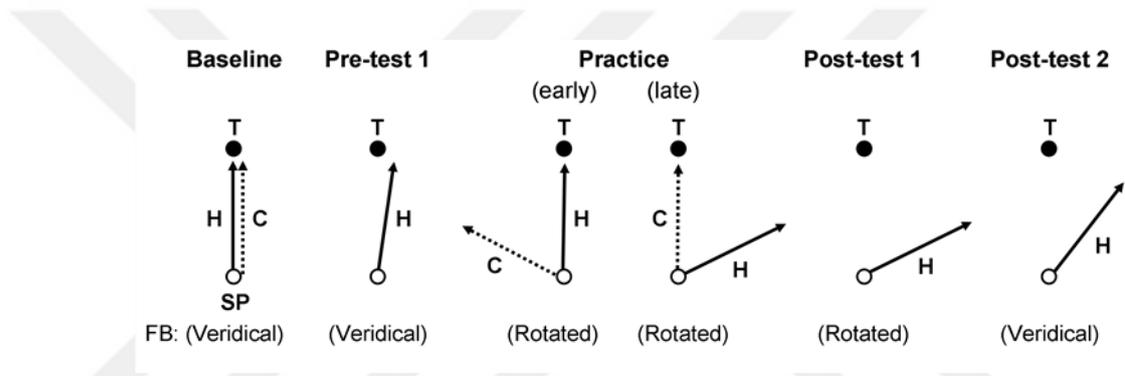
Figure 2. Hand movement (H), the starting position (SP) and the target (T) in linear rotation angles with 30, 75, and 150 degrees. Adapted from "Eye-hand coordination during visuomotor adaptation with different rotation angles" by S. Rentsch and M.K. Rand, 2014, *PloS ONE*. Copyright 2014 Rentsch, Rand.

adaptation. Since the utilized task in Study 2 is identical with Study 1 and performance in this task is exceptionally relied on manual movements; understanding the neural bases of visuomotor adaptation is highly crucial.

1.5.1. Neural Bases of Motor Skill Learning and Visuomotor Adaptation

Prior to explaining neural bases related to sensorimotor adaptation/visuomotor adaptation, it would be logical to mention control-based learning theory (COBALT), which suggests that motor skill learning is directly an extension of motor control process and provides some insight into neural representation of motor skill learning (Willingham, 1998). COBALT posits that there are three principles for motor control: (1) neural separability principle; (2) disparate representation principle; and (3) dual mode principle. Neural separability principle suggests that cognitive elements of motor control are attended by different regions in the brain. Separate processes are included in motor control. First one is referred to as strategic process, stated to occur in dorsolateral prefrontal cortex. Perceptual-motor integration process is the second process, and this process is thought to be located in parietal lobe and premotor cortex. Third is the sequencing process which is based in supplementary motor area and basal ganglia. And finally, dynamic process, thought to be based in spinal cord. The second principle, disparate representation principle proposes that the four processes mentioned above take different representation forms. During strategic process, the goal is determined in a given context. Perceptual-motor integration is involved in target selection. Sequencing process takes part in planning the action. And dynamic process indulges with learning novel spatial and temporal cues related to motor activity. The third principle, dual mode principle, suggests that these processes can occur in two modes: the unconscious mode and the conscious mode. Willingham proposes that the conscious mode is generally active when individual thinks he/she will fail during performance and other than that, the processes occur in unconscious mode.

Studies conducted to investigate the underlying neural mechanisms of adaptation to a visuomotor rotation have suggested contributions of multiple cortical and subcortical areas of the brain. Contributions were provided by the prefrontal cortex, parietal cortex, primary motor cortex, and cerebellum during early phases of visuomotor adaptation and through the later phases of adaptation there is a shift

towards parietal and temporal areas (Imamizu et al., 2000; Krakauer et al., 2004; Miall et al., 2001; Seidler et al., 2006).

Cerebellum plays a significant role in motor control not only with direct involvement but also with indirect involvement such as facilitating the acceleration of adaptation to sensorimotor transformations (Seidler, 2010). The acceleration of adaptation is useful for the organism as failure to swiftly adapt to changes in the environment might have undesired consequences in real life. The contribution of primary motor cortex is also crucial as it generates neural impulse for movement control (Chase et al., 2012). It can be understood that the command for movement comes from primary motor cortex since previously mentioned motor neurons are densely localized in this region. Parietal cortex seems to display high activity during visuomotor adaptation and is thought to provide a general visuospatial computation (Krakauer et al., 2004). This visuospatial computation is crucial not only for sensorimotor integration but also formation of a strategy to successfully perform the required movement in the given context. Prefrontal cortex, which is formed of dorsolateral, ventrolateral and orbitofrontal cortexes, contributes greatly to formation of connection between sensory and motor systems during visuomotor adaptation (Goldman-Rakic, 1987).

The involvement of prefrontal cortex might be resulting from the fact that visuomotor adaptation is thought to be associated with not only sensorimotor integration but also some cognitive functions like working memory and visuospatial attention (Taylor and Thoroughman, 2007; Anguera et al., 2010). Visuospatial attention and spatial working memory was suggested to play a crucial part in initial stages but not for late stages of visuomotor learning (Fernandez-Ruiz et al., 2011). This coincides with the statements made above related to the role of prefrontal cortex during early phases of visuomotor adaptation. This is highly reasonable since after adaptation occurs the need for high visuospatial attention and spatial working memory will tend to decrease. Individuals will achieve mastery of the sensory-motor map at this stage. Moreover, according to Wolpert and colleagues (2011), early phases of motor learning are more cognitively driven than later stages. This might be caused by two factors: first is the conscious attention paid to possible mistakes as either the environment or the task is unfamiliar, and second may be related to the effort spent to produce a cognitive strategy for task fulfillment. Willingham (1998)

proposed that during motor skill learning the prefrontal cortex is activated when the activity occurs in conscious mode, more clearly, when participants have initial encounter with the task the information is kept in working memory for a while actively used to direct movements. This statement supports the active role of prefrontal cortex in early stages of visuomotor adaptation as behavioral planning related to action takes place in the prefrontal cortex during acquisition of a new motor skill (Tanji and Hoshi, 2001).

Some neuroimaging studies revealed that especially dorsolateral prefrontal cortex (DLPFC), located in prefrontal cortex, is involved in sensorimotor adaptation tasks (Floyer-Lea and Matthews, 2004), and that this activation is observed in early stages of adaptation (Halsband and Lange, 2006). These findings were supported by studies conducted on the following years (Gentili et al., 2010; Seidler and Noll, 2008). Since dorsolateral prefrontal cortex is a part of prefrontal cortex it would be logical to observe activity of DLPFC in initial phases too.

Similarly, the involvement of ventrolateral prefrontal cortex (VLPFC) was also demonstrated during motor activity control and inhibition of motor behavior (Levy et al, 2011). Thus, it would be possible observe this activity in VLPFC during first phases of visuomotor adaptation since when participants are presented with an unfamiliar sensorimotor rule, the reliance on motor activity control will be high and during this phase inhibition of a previously learned unmodified movement might also take place.

1.5.2. Hemodynamic Response

Any activity in the brain results in a necessity for cerebral blood flow (Rahman and Ahmad, 2016). Liao and colleagues (2013) define this process as neurovascular coupling during through which a hemodynamic response is produced. Neural activity-dependent changes in cerebral blood, in other words oxygenation state of hemoglobin in the region serves as an indicator of neural activity (Disbrow et al., 2000). Disbrow and colleagues also suggest that as neural activity requires oxygen, it leads to an increase in oxygenated hemoglobin and deoxygenation occurs when oxyhemoglobin gives up its oxygen.

There are various imaging technologies that can detect the changes in concentration related to oxygenated hemoglobin (oxy-Hb) and deoxygenated

hemoglobin (deoxy-Hb). This is possible by the optical properties that both oxy-Hb and deoxy-Hb possess and even though near-infrared light between 650 and 950 nm is not successfully absorbed by the skull and skin, oxy-Hb and deoxy-Hb remain outside this limitation (Wray et al., 1988). Functional magnetic resonance imaging (*f*MRI) and positron emission tomography (PET) can be stated among these imaging technologies. Several studies proved that underlying neural mechanisms related to cognition and emotion can be examined using *f*MRI and PET (Cabeza and Nyberg, 2000; Davidson and Sutton, 1995). Moreover, *f*MRI and PET were also used to investigate the neural correlates of visuomotor adaptation and rotation learning (Anguera et al., 2007; Krakauer et al., 2004). On the other hand, *f*MRI is very expensive, sensitive to motion and restricts individuals' movements and PET requires injecting radioactive tracer and also shows sensitization to movement (Izzetoglu et al., 2005).

Functional near-infrared spectroscopy (*f*NIR) provides simultaneous measurement of local oxy-Hb and deoxy-Hb concentration using specific wavelengths of light which allows for noninvasive measurement and it has some advantages over *f*MRI as it is less sensitive to motion artifact, it is cheaper and it provides better temporal resolution (Rahman and Ahmad, 2016). Temporal resolution is referred to as the length of time needed to return and record data from a specific location (Théau, 2008). The changes in oxy-Hb and deoxy-Hb concentrations obtained via *f*NIR can be determined by using Modified Beer Lambert law (MBLL). MBLL provides a comparison related to oxy-Hb and deoxy-Hb concentrations between the baseline and task periods (Baker et al., 2014). Thus, MBLL makes it possible to observe relative changes in oxy-Hb and deoxy-Hb during baseline and task performance. Therefore; *f*NIR is a competent device for hemodynamic response measurements, not only because its capability of measuring local oxy-Hb and deoxy-Hb concentrations, but also availability that is provided by the device to distinguish the responses produced during non-task and task periods.

A study conducted by Gentili and his colleagues (2010), utilized *f*NIR to investigate hemodynamic correlates of visuomotor adaptation during a "center-out task", which is related to visuomotor rotation learning. The sample of the study consisted of five participants, all of whom were right-handed. The task required participants to draw lines between targets presented on the digitizing tablet to link

them using an appropriate pen. During participants tried to link the targets a counter-clockwise linear rotation of 60 degrees was applied on the cursor. Movement time (MT) and movement length (ML) throughout 20 blocks (180 trials) were included as the behavioral data for the analysis. There were four peripheral targets located around a central target and movements were initiated from the central target. Hemodynamic responses produced throughout the experiment were recorded using a 16-Channel *f*NIR sensor-pad which was located on participants' forehead. The authors included averages of oxygenated hemoglobin (oxy-Hb) and oxygenation change (OXY), obtained from the difference between oxy-Hb and deoxy-Hb concentrations, for each trial block and focused on overall change in dorsolateral prefrontal cortex. Results indicated a significant decrease in oxy-Hb and oxygenation change from early to late phases of adaptation. This study provided some insight into this study as it demonstrated that changes in hemodynamic response can be interpreted for various phases of visuomotor adaptation and that *f*NIR device can efficiently measure the changes in hemodynamic response during adaptation to a visuomotor adaptation task occurs.

1.6. Overview of Literature for Study 1 and Study 2

To summarize, the preservation of a performed motor action is achieved by organisms' capacity to learn, which requires integration of the obtained sensory cues with motor action along with necessary amount of practice related to this action. This is achieved by an internal model which records and maintains the input and output characteristics of the learned behavior for future usage, eliminating the need for a wide space in the brain for preserving each component of individuals' motor behavior repertoire. The schema theory put forward by Schmidt (1975) was more sufficient in explaining the supply of predetermined sets of rules and the capability of the motor program in updating itself to adapt to changes in the environment.

Based on the influential factors on motor skill learning, several conclusions were drawn. First one is that implicit learning is more facilitative in skill learning with regards to the performance produced by the individual and explicit learning strategies might result in improvement solely for the comprehension of the presented task. Secondly, as it was also suggested by Ebbinghaus (1964), spaced trainings promote performance, and therefore inter-trial interval is significant in motor skill acquisition. Third is related to length of inter-trial interval which should be around 5

seconds minimum for improved adequacy of performance. Fourth is that assistance during motor skill learning might result in deterioration in performance as individuals will not be as much involved with the task as they would be during self-controlled practice. And finally, frequent feedback related to motor action will result in a lack of strategy formation related to the task as too much reliance will be placed on the received feedback. The evaluations made on the influential factors during skill acquisition provided assistance when conducting the present study. With the aim of facilitating acquisition of the motor skill related to the task in the present study; the form of learning was preserved as implicit, spaced training was used, inter-trial interval was set at 5 seconds, no assistance was provided during task performance and no feedback was given to control for the probable effects of feedback on movement strategies.

The fact that multiple cortical and subcortical areas of the brain have distinctive contributions to visuomotor adaptation supported Willingham's neural separability principle, which stated that cognitive elements of motor control are associated with different brain regions. The involvement of prefrontal cortex during early phases of visuomotor adaptation was emphasized since visuomotor adaptation also relates to working memory and visuospatial attention. Prefrontal cortex was stated to contribute in visuomotor adaptation process during the early stages of learning rather than later stages. Willingham explained this with assistance of working memory as the storage to be used for movement until a sufficient cognitive strategy is produced. Within the areas located in prefrontal cortex, DLPFC was thought to be the one which was especially active during visuomotor adaptation and that this activation took place only during initial phases of motor learning. Motor activity control and inhibition of motor behavior are thought to be increased during early stages of learning and therefore it is possible to expect neural activity in VLPFC as well.

Hemodynamic response is produced as a result of cerebral blood flow caused in an activated region and the changes in concentration regarding oxygen were measured with density of oxygenated hemoglobin and deoxygenated hemoglobin in the local area. Among the imaging technique used in measuring hemodynamic activity like *f*MRI, PET and *f*NIR; functional near-infrared spectroscopy (*f*NIR) is cheaper than others, it is less sensitive to motion artifact and it does not necessitate

injection of radioactive tracker like PET does. Plus, *f*NIR provides better temporal resolution, which is referred to as the capability of a device in capturing swift motions of an object (Lin and Alessio, 2009), than *f*MRI. Based on the adequacy of functional near-infrared spectroscopy (*f*NIR) in recording the hemodynamic response produced during visuomotor adaptation in addition to its cheaper price, lesser sensitivity to motion artifact and better temporal resolution; it was determined as neuroimaging technique for this study. The utilized *f*NIR device had a sensor-pad receiving hemodynamic response from 16 active channels and it was capable of monitoring dorsal and inferior frontal cortical areas (Ayaz, 2010). The device was thought to supply sufficient information since initial activity during a novel visuomotor rotation task, as it was previously stated, occurs in prefrontal cortex.

Some of the experiments conducted to reveal the contribution of foveal guidance during various visuomotor conditions utilized goal-directed reaching or pointing tasks (Lackner and Dizio, 1994; Newell and Rosenbloom, 1981; Krakauer et al., 1999). Sailer and colleagues (2005) provided an argument related to these types of tasks based on their inability to trigger an exploratory stage since reaching behavior is frequently encountered in daily life and a visuomotor mapping rule related to this behavior is already present in individuals' behavior repertoire. Owing to this fact, it would not be logical to think these types of tasks to necessitate generating new strategies for a novel mapping rule, since there will be a swift betterment in performance after initial attempts. From this point of view, Sailer and colleagues (2005) utilized a highly complex visuomotor rotation task by requiring usage of both hands in addition to necessitating adaptation to cylindrical handles as a novel tool. Participants had to adapt to this novel tool and manually direct it to achieve the desired position for target hit. Foveal responses measured throughout the study revealed that participants' eyes shifted towards the next target before manual response was completed. On the other hand; Rentsch and Rand (2014), suggested that the task utilized by Sailer and colleagues was extremely complex and thus changes that occur in visual guidance following adaptation cannot be generalized to traditional tasks of visuomotor adaptation. In traditional tasks of visuomotor adaptation there is a manipulation related to amplitudes or trajectories of manual movements and such a complex tool might result in particular and unique foveal responses, therefore; rather than a modification of a previously learned visuomotor

mapping rule, learning related to a highly complex novel rule takes place. According to Rentsch and Rand, a muscular-skeletal system related to more simple tools are already used in daily life and a less complex tool usage would results in more generalizable results. Based on this, they employed a trajectory manipulation requiring computer mouse usage and this trajectory manipulation occurred in multiple degrees, which was previously explained. Since multiple degrees of visuomotor rotation are suggested to differentiate in terms of underlying adaptive processes (Cunningham, 1989; Hinder et al., 2008); Rentsch and Rand hypothesized that changes in visual guidance provided by the eye might also be influenced by the degree of manipulation. Indeed, they were able to reveal distinguished gaze behavior between 30-75 degrees and 150 degrees of rotation manipulation. However; the rotation manipulation applied in this study was a modification in the visual feedback provided to participants, rather than a genuine modification in the direction of the cursor (e.g. Krakauer et al., 2005).

The studies mentioned in previous sections and many more have investigated visuomotor rotation adaptation to enlighten the issues of generalization of learning related to a degree of trajectory to other degrees of trajectory, or to detect the errors made by participants during adaptation to different degrees of trajectory. Each of the experiments conducted by Rentsch and Rand, Sailer and colleagues, and Abrams and colleagues, which were mentioned in detail previously, have revealed significant information related to the relationship between visual information and manual action by investigating the role of visual cues, changes in gaze behavior and exploratory and predictor point of view for the eyes during adaptation to a visuomotor rotation task occurred. Nevertheless, the task utilized by Abrams and colleagues was primarily applied to emphasize the contribution of visual guidance rather than components of eye-hand coordination and Sailer and colleagues' task was too complex to generalize to changes in eye-hand coordination occurring in less complicated behaviors such as computer mouse usage. Even though Rentsch and Rand examined the adaptive changes in eye-hand coordination during visuomotor adaptation, since their main focus was generalizability of the results, they remain within the limitations of traditional visuomotor mapping rules. Moreover; Rentsch and Rand provided no information related to how these adaptive changes would occur if the manipulation was not made on the feedback but directly on the cursor. A

decade earlier than Rentsch and Rand's study, Krakauer and colleagues applied the cursor manipulation however eye-hand coordination was not among the aims of the study. Therefore; the adaptive changes in eye-hand coordination in a visuomotor rotation task which applies genuine trajectory manipulation on the cursor remain unclear.

As for the neural correlates of visuomotor rotation, the measurements can be taken either based on hemodynamic response produced during adaptation process (via *f*MRI and *f*NIR) or the received electroencephalographic signals (via EEG). Anguera and colleagues (2010) used *f*MRI to record hemodynamic responses during adaptation to a 30º of clockwise rotation in the visual feedback of the cursor and revealed activity in DLPFC, located in prefrontal cortex. As it was previously argued; providing modified visual feedback might not be the same as literally encountering the trajectory manipulation and performing it through the cursor. Gentili and colleagues (2008) utilized electroencephalographic signals to make inferences during visuomotor adaptation process and applied genuine rotation manipulation on the cursor with a 60º of counter-clockwise rotation. They revealed increased activation in temporal and frontal lobes correlating with improvement performance, but no specific location related to this activity. Gentili and his colleagues (2010) utilized the same task again in another study; however the neuroimaging technique was *f*NIRs this time. The study provided further proof to the possibility that hemodynamic response produced during adaptation to visuomotor rotation task can be accurately recorded and investigated via *f*NIR device. The problem with this task used by Gentili and colleagues (2008 and 2010) was that they allowed the participants to choose one of the four peripheral targets located around a main target where movement was initiated. While visuomotor adaptation is a more implicit and unconscious process, target-selection occurs in a highly conscious level (Willingham, 1998), which contradicts the nature of visuomotor adaptation process.

An overall view of the studies reviewed above, regarding notions of both eye-hand coordination and hemodynamic correlates, reveals that the applied tasks are either too complex for generalization of change patterns observed in the obtained measurement or they tend to remain within the limits of traditional trajectory manipulations. This, in fact, left them with a limited understanding of the adaptation process since these trajectories were related to the same internal representation; that

is a visuomotor mapping rule of linear trajectory. In a study conducted by Wigmore and colleagues (2002), it was revealed that multiple degrees of traditional trajectory manipulation competed for the same internal model as adaptation to a specific degree of trajectory manipulation was diminished after participants were trained with another degree of trajectory manipulation. Thus, these studies were able to account for the phases of motor learning during a traditional visuomotor rotation trajectory and the differences that might occur during transformation and integration procedures with a novel visuomotor mapping rule still remains unclear. Plus, they failed to provide insight into how the changes in eye-hand coordination and hemodynamic measurements would occur during a novel kind of trajectory manipulation, other than linear trajectory manipulation.

In order to observe the potential changes in phases of motor learning during a novel visuomotor mapping rule, in this study, not only the application of trajectory manipulation was used, but also the trajectory itself was manipulated. In addition to CCW linear trajectory changes, a CCW nonlinear/circular trajectory manipulation was utilized as an alternative for traditional trajectory manipulation. Within the scope of this study, two experiments were conducted; Study 1 to investigate eye-hand coordination during learning of a novel visuomotor mapping rule and Study 2 to examine the underlying neural processes of adaptation to a novel visuomotor mapping rule. In both of the studies, adaptation to linear and circular trajectories was examined not only individually, but also a comparative analysis was made between these trajectories regarding changes in eye-hand coordination and hemodynamic activity.

1.7. Research Questions and Hypotheses of Study 1 and Study 2

In both Study 1 and Study 2, along with previously used linear visuomotor rotation tasks that only apply linear trajectory manipulation on the cursor, a circular visuomotor rotation task was also prepared and utilized. The circular visuomotor rotation task provided an alternative for traditional visuomotor rotation tasks and visuomotor mapping rules. This was obtained by not only manipulating the trajectory of the cursor but also modifying the trajectory itself to follow a circular pattern which will be explained in detail in the method section of the study. The tasks were presented as five consecutive trials and the length of time participants spent to complete visuomotor rotation trials was included as the behavioral data for the

analysis. Research questions and hypotheses related to trial completion length are common for Study 1 and Study 2, which are stated below.

Research Question 1: How does the length of time participants spend to complete visuomotor rotation trials gradually change over time?

Research Question 2: Does the overall length of time participants will spend to complete all trials will differ between experimental conditions (Linear visuomotor rotation and circular visuomotor rotation)?

Research Question 3: Does the gradual change over time regarding the length of time participants spend to complete trials differ between experimental conditions (Linear visuomotor rotation and circular visuomotor rotation)?

Hypothesis 1: The gradual change over time regarding the length of time participants will spend to complete visuomotor rotation trials will occur in a decreasing pattern.

Hypothesis 2: The overall length of time participants will spend to complete all trials will be higher for circular visuomotor rotation condition than linear visuomotor rotation condition.

Hypothesis 3: The gradual change over time regarding the length of time participants will spend to complete trials will differ between experimental conditions (Linear visuomotor rotation and circular visuomotor rotation).

The aim of Study 1 was to investigate eye-hand coordination during adaptation to a linear visuomotor rotation task and circular visuomotor rotation task throughout trials with the addition of a comparison between the two tasks to find out whether they had distinct influences on eye-hand coordination. Guidance provided by the eye to hand was analyzed with an eye-tracking system. Changes in eye-hand coordination related to tasks were examined not only based on the global adaptation process, but also on local changes like time interval between first eye-fixation on target and target hit (eye-to-shooting latency), time interval between first eye fixation and cursor arrival on target (eye-to-hand latency), time interval between cursor arrival on target and target hit (hand-to-shooting latency) and time interval between eye fixation on target and eye fixation on the next target (eye-to-eye latency) that were considered to contribute to the global adaptation process. Research questions and hypotheses related to eye-hand coordination are stated below.

Research Question 4: How do the local components of eye-hand coordination stated as eye-to-shooting latency, eye-to-hand latency, hand-to-shooting latency and eye-to-eye latency gradually change over time?

Research Question 5: Does the overall change in the local components of eye-hand coordination stated as eye-to-shooting latency, eye-to-hand latency, hand-to-shooting latency and eye-to-eye latency in all trials differ between experimental conditions (Linear visuomotor rotation and circular visuomotor rotation)?

Research Question 6: Does the gradual change over time regarding the local components of eye-hand coordination stated eye-to-shooting latency, eye-to-hand latency, hand-to-shooting latency and eye-to-eye latency differ between experimental conditions (Linear visuomotor rotation and circular visuomotor rotation)?

Hypothesis 4: The gradual change over time regarding the local components of eye-hand coordination stated as eye-to-shooting latency, eye-to-hand latency, hand-to-shooting latency and eye-to-eye latency will occur in a decreasing pattern.

Hypothesis 5: The overall change in local components of eye-hand coordination stated as eye-to-shooting latency, eye-to-hand latency, hand-to-shooting latency and eye-to-eye latency in all trials will be higher for circular visuomotor rotation condition than linear visuomotor rotation condition.

Hypothesis 6: The gradual change over time regarding the local components of eye-hand coordination stated as eye-to-shooting latency, eye-to-hand latency, hand-to-shooting latency and eye-to-eye latency will differ between experimental conditions (Linear visuomotor rotation and circular visuomotor rotation).

Study 2 aims to examine the underlying neural mechanisms of visuomotor adaptation to a linear rotation and circular rotation tasks during performance based on the hemodynamic response changes and to interpret these changes related to various types of rotation and phases of adaptation. Changes in hemodynamic response were examined related to the concentration of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) in participants' prefrontal cortex which were obtained via *f*NIR device. Research questions and hypotheses related to hemodynamic response during visuomotor adaptation are provided below.

Research Question 7: How do oxy-Hb and deoxy-Hb concentrations gradually change over time?

Research Question 8: Does the overall change in oxy-Hb and deoxy-Hb in all trials differ between experimental conditions (linear visuomotor rotation and circular visuomotor rotation)?

Research Question 9: Do the gradual changes over time regarding oxy-Hb concentration and deoxy-Hb concentration differ between experimental conditions (linear visuomotor rotation and circular visuomotor rotation)?

Hypothesis 7: Oxy-Hb concentration and deoxy-Hb concentration will demonstrate gradual changes throughout consecutive trials.

Hypothesis 8: The overall change in oxy-Hb and deoxy-Hb in all trials will differ between experimental conditions (linear visuomotor rotation and circular visuomotor rotation).

Hypothesis 9: The gradual changes over time regarding oxy-Hb concentration and deoxy-Hb concentration will differ between experimental conditions (linear visuomotor rotation and circular visuomotor rotation).

Overall purpose of the study, including Study 1 and Study 2, is to provide a comprehensive analysis related to a novel trajectory manipulation based not only on the guidance provided by visual cues but also on the underlying neural process during task performance. In addition to this, it is aimed to offer a comparative analysis regarding traditional trajectory manipulations and circular trajectory manipulation within the scope of eye-hand coordination and hemodynamic response.

CHAPTER II

Method

There are two studies within the scope of this thesis and therefore; the method section is divided into two parts. Study 1 was conducted with the aim of investigating eye-hand coordination during adaptation to a novel visuomotor rotation task. And Study 2 was carried out for examining the underlying neural mechanisms of adaptation to a novel visuomotor rotation task by utilizing hemodynamic response changes during this process. Thus, this section of the thesis provides information related to the participants, experimental equipment, procedure, data acquisition and data preparation for Study 1 and Study 2.

2.1. Study 1

2.1.1. Participants

The sample of the study consisted of 32 participants (16 males and 16 females) aged between 18 and 50 ($M_{age} = 24.46$, $SE_{age} = 6.13$). Participants of the study were students and lecturers recruited from Izmir University of Economics. All of them read the participant information form and signed the informed consent before agreeing to participate (Appendix A-B). Whether participants had any neurological or psychological disorder, color blindness or any kind of serious visual disorder was determined via participant evaluation form (Appendix C). Each of these characteristics was determined as exclusion criterion for the study. For the clarity of data obtained from Eye-Tracker device, individuals who used eyeglasses or contact lenses were also not included in the study. Participants' tendencies for hand usage were examined with Edinburgh's Handedness Inventory (Oldfield, 1971) (Appendix D). Only right-handed participants were included in the study to prevent potential differences caused by hand usage. Based on this, participants were formed of healthy, right-handed individuals who had normal vision. Participation for the study was voluntary and no payment was provided in return. The assignment of participants to experimental conditions was carried out coincidentally.

2.1.2. Apparatus/Materials/Equipment

Experimental sessions were carried out in a sound, warmth and lightproof test chamber individually and recorded without interruption by a previously set camera system. In the test chamber there was a comfortable seat, height and back angle of which would be rearranged for each participant. The seat was placed in front of a table. The Remote Eye-Tracking Device (RED250, SensoMotoric Instruments, Inc., Boston, MA, USA), mounted under an LCD monitor of 22", was placed on the table. iView X system (SensoMotoric Instruments, GmbH. http://www.smivision.com) was used to record the gaze tracking data. iView X was installed on a laptop which was available in the SMI package. The laptop was placed next to the Remote Eye-Tracking Device. A box was utilized to uplift the monitor 7 cm from the table so that the device was aligned with participants' eye level. Computer mouse was put next to the monitor to be used for controlling the cursor during visuomotor rotation tasks. In order to minimize measurement errors that might result from participants' head movements, a chin rest was applied. SMI Experiment Center version 3.4 (SensoMotoric Instruments, GmbH. http://www.smivision.com) was used for the presentation of instructions, calibration procedures, presentation of visuomotor rotation tasks, and recording of manual and foveal activities. SMI Experiment Center was installed on the LCD Monitor so that participants' gaze tracking data during calibration and visuomotor rotation tasks could be saved by the Remote Eye-Tracking Device, mounted under the monitor. The cable with yellow circle was inserted in the USB Port of the laptop which connected iView X with the Remote Tracking Device. Plus, network configuration settings needed to be made to connect iView X and the LCD Monitor. Through these settings found in "hardware" section, listening interface was defined as the laptop and the monitor was defined as the source sending UDP packets to interface. The instruction of visuomotor rotation task was created as text file. Calibration process was already available in the program which included a 13 point drilling algorithm. The background color of the calibration screen and the size and color of the moving point were designed to be identical to the background and target points in visuomotor rotation task. Visuomotor rotation task was uploaded to the program as an exe file which started running automatically after calibration was completed. Visuomotor rotation tasks were implemented using C# programming language on Visual Studio 2015 Community. The tasks were presented

and behavioral responses were recorded via Unity version 5.3.1 (Unity Technologies. Unity 3d. http://unity3d.com/).

The task involved fifteen targets all of which were present on the screen throughout the trials. The targets formed a circle and a crosshair was right at the middle of this circle standing at the same distance from all of the targets. The crosshair could be controlled with the computer mouse and targets were hit with the crosshair. The targets were unfilled small circles and they were filled with red color when they turned into imminent targets. Only one of the targets were turned red at a time, and remained red until it was hit. The background color of the visuomotor task was blue (R = 44, G = 77, B = 121), the line color of the unfilled targets and the crosshair were green (R = 0, G = 176, B = 80), finally the indicator of the target was simple red (R = 255, G = 0, B = 0). A timer was placed on the top left of the screen and kept on counting throughout the experiment.

2.1.3. Procedure

Participants who were invited to test chamber were briefly informed about the experiment and walked through the informed consent with the researcher. Upon agreeing to participate, they were instructed to answer the questions in the demographic information form. After they filled the form, participants were evaluated based on elimination criteria. If thought as fit, they were given Edinburgh Handedness Inventory to determine their tendency of hand usage and right-handed participants continued to the experiment. All of the participants were reminded that at any time of the study they were free to leave or refuse to participate.

2.1.3.1. Eye Tracker Procedure

Necessary arrangements were made in order for the participant to seat at the chair comfortably and at appropriate height. If there was make-up on participants' eye-lashes and eye-lids, it was kindly removed with a cotton wool using a make-up remover solution as make-up was proven to have distortive effects on foveal data (O'Brien, 2009). Then, participants were told to place their chin on the chin rest and look directly to the monitor. After that, iView X was started on the laptop located next to the monitor. iView X provided instructions with arrows regarding where the eyes should be located for quality data acquisition. The arrows were located on all four sides of the screen. For the top and bottom of the screen inward arrows indicated

that participants should be closer to the monitor while outward arrows signaled necessity for more distance. The arrows on the sides of the screen pointed to left or right indicating movement towards that direction (Figure 3). With the help of the arrows, chin rest was rearranged for participants provided that the distance between chin rest and the monitor was maintained within 60-80 cm, based on producer companies' test data. This distance was measured and noted for all participants.

Following this arrangement, calibration was carried out for each participant via SMI Experiment Center. Participants were instructed to follow the moving point with their eyes as punctually and sharply as possible. The stimulus moved to 13 points on the screen and fixated at each point for 500 msec. In a case when diversions from the fixated point exceeded 0.80 on either x or y axis, the procedure was repeated. The experiment continued only after this criterion was met. With this method the individual differences between participants were aimed to be compensated for.

Following the calibration process, a text file was opened and participants could see and read the necessary instructions to perform the visuomotor rotation task. They were told to click right or left mouse button to begin. After they clicked on the mouse, Unity.exe file including visuomotor rotation task was automatically started by SMI Experiment Center (Figure 4).

2.1.3.2. Visuomotor Rotation Task

The visuomotor rotation task required participants to hit fifteen stable targets located around an imaginary circle as swiftly as possible and without mistake using the right click button of the computer mouse (Figure 5-A). A crosshair was presented to represent the movements made by computer mouse and it was located in the middle of the circle at the beginning of the trial. The imminent target among these targets was demonstrated by a change of color. Imminent target was turned into red and at the same time a timer started counting on top left of the screen. After the first target was hit, next target simultaneously turned into red. The order of the targets was arranged in such a pattern that the distance between successive targets were equal to each other. After all of the fifteen targets were hit, the first trial was completed. Timer stopped counting for the first trial and was fixed at its place. The same procedure was repeated during all of the trials.
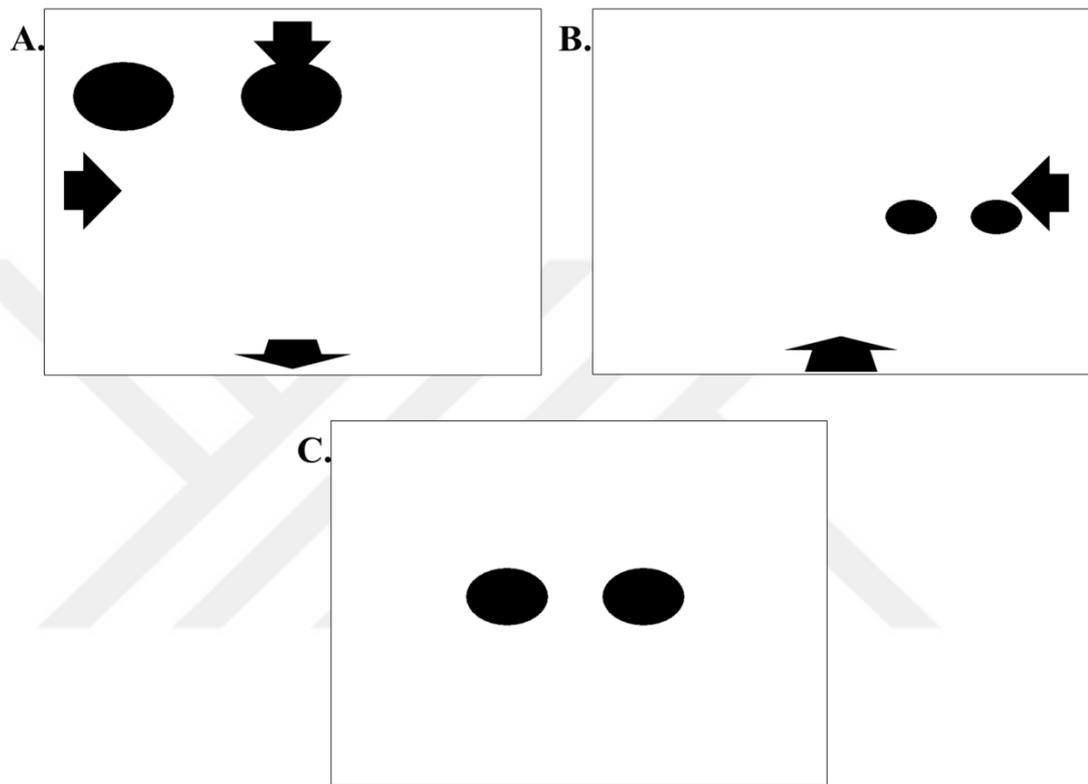
Figure 3. SMI Experiment Center (A) The location of the eyes are too high, too aligned to left and too close to the monitor (B) the location of the eyes are too aligned to right and too far from the monitor (C) appropriate location of the eyes during data acquisition
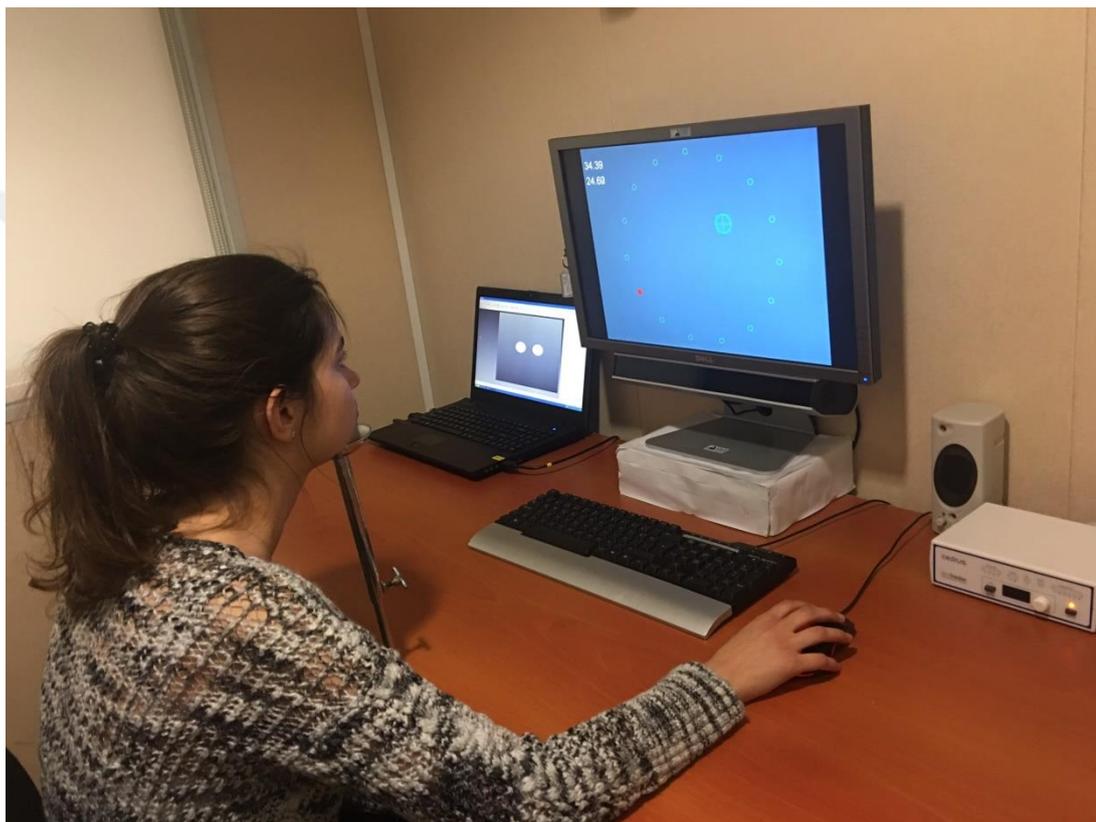
Figure 4. Experimental Setup for Study 1
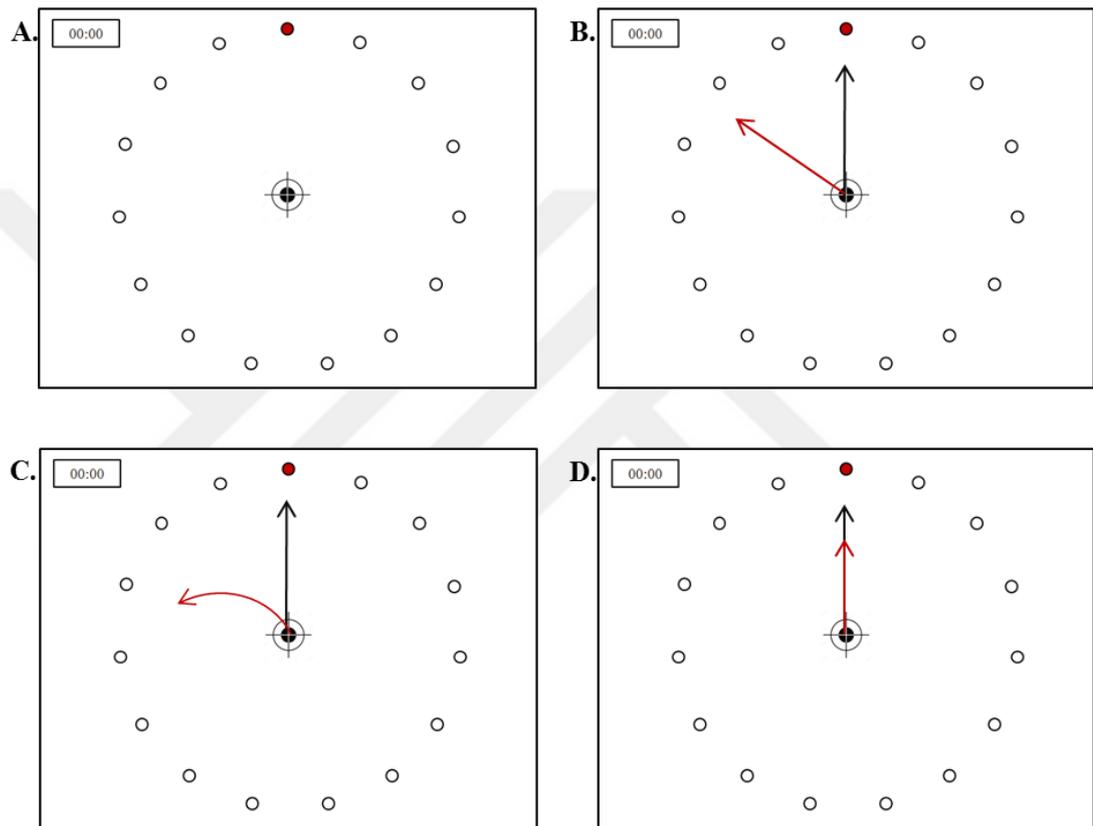
Figure 5. Illustration of visuomotor rotation task (A) the environment of the task (B) linear visuomotor rotation task (C) circular visuomotor rotation task (D) baseline trial with no rotation manipulation

The experimental conditions were determined as linear visuomotor rotation and circular visuomotor rotation. In linear visuomotor rotation condition, there was a counter-clock wise (CCW) diversion in the trajectory of the cursor and this trajectory occurred in a linear pattern. In other words, straight movements participants made using the crosshair resulted in counter-clock wise linear trajectory (Figure 5-B). By adapting to this rotation manipulation, participants were expected to hit all of the fifteen targets. The rotation continued without interruption throughout the trial. When participants hit one target, the path of the crosshair was still manipulated until it reached the next target and so on.

In circular visuomotor rotation the cursor's trajectory was again diverted counter-clock wise. However, this time rotation in the movements occurred in a circular pattern. More clearly, while participants moved the crosshair straight, the path of the crosshair was diverted in circular trajectory (Figure 5-C). As in linear visuomotor rotation condition, diversion in cursor's trajectory was maintained throughout the trial and at every location on the screen.

With the aim of controlling training effects on linear and circular visuomotor rotation tasks, the experimental design was preferred to be between-subjects design. However, prior to visuomotor rotation trials, following their assignment to either linear or circular conditions, participants in both conditions completed a single baseline trial. In the baseline trial no manipulation was employed on the cursor's trajectory and the crosshair performed intended movement on intended direction (Figure 5-D). This baseline trial served as both an adaptation phase to environment of the task and a measurement which provided initial performance of participants on a target-hit task.

In both conditions, participants were not informed of the manipulation on the cursor's trajectory in advance, thus they were expected to develop a strategy to perform the desired movement. No assistance was provided during the experiment. They completed equal number of trials in both linear visuomotor rotation condition and circular visuomotor condition. The number of trials was specified as five consecutive trials in order to prevent the effects of fatigue on performance. There was a resting period of 5000 ms between each trial. Participants in linear condition were presented with six trials including one baseline trial and five linear visuomotor rotation trials and participants in circular condition were asked to complete also six

trials with one baseline trial and five circular visuomotor rotation trials (Figure 6). After all of the trials were completed, participants were thanked for their part in the study and the study was ended.

2.1.4. Data Acquisition

Throughout the study, SMI Experiment Center recorded saccades, fixations and eye-blinks as foveal reactions obtained via Remote Eye-Tracking Device. And manual movements of participants were obtained as mouse clicks at any point of the screen during the tasks. Foveal reactions and mouse clicks were collected with specific coordinates on x and y axis. These coordinates provided necessary information for determining areas of interest during analysis. Areas of interest can be defined by the researcher based on which locations on the screen are crucial for the study. Once specified, an area of interest provides information about foveal and manual activity on that location. In this study, target locations in visuomotor rotation task were determined as areas of interest. Moreover, SMI Experiment Center also provided a screen record file in which the whole eye and hand movements were preserved. This file had the same time stamp as the experiment and allowed analyzing changes that took place in milliseconds.

Unity.exe file recorded how long it took for a participant to hit each target and the overall length of time participants spent to hit all fifteen targets. On each trial time runner was reset and target hits were presented in a cumulative form increasing from zero to above. Finally, length of time to complete six trials (baseline and rotated) were gathered in each trial and for all participants, who were in either linear or circular condition.

An application chart was used to preserve information related to each participant's age, experimental condition, contact address, distance between chin rest and monitor, and finally diversions from x and y axes during calibration phase.

2.1.5. Data Preparation

2.1.5.1. Preparing Behavioral Data for Analysis

The length of time between each target hit, and the time when last target was hit were recorded by Unity. Using this data, how long it took participants to complete a single trial was calculated using Microsoft Excel 2010. The data then was prepared
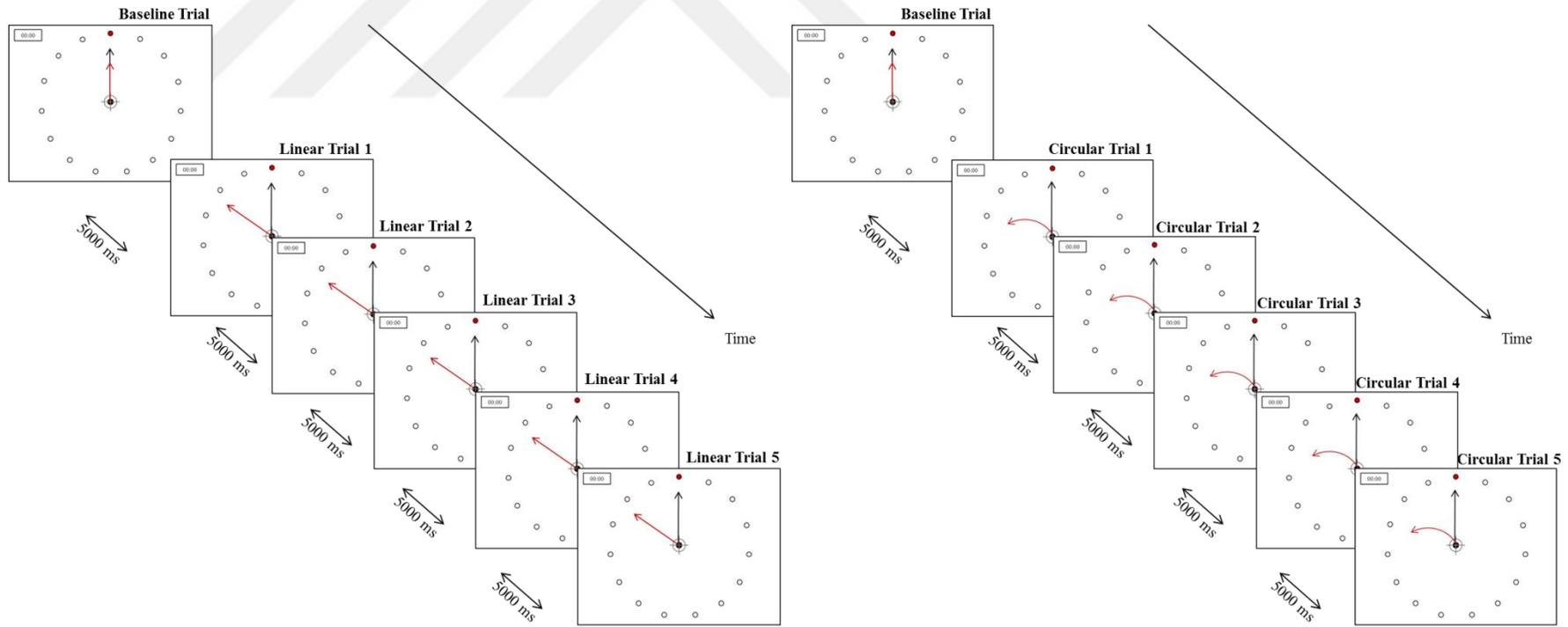
Figure 6. Flow diagram of linear visuomotor rotation task (left) and circular visuomotor rotation task (right)

for multilevel analysis by placing participant ID, consecutive trials, experimental condition and trial completion time on columns and each participant on rows. This type of arrangement of the data is referred to as long data format.

2.1.5.2. Preparing Foveal Data for Analysis

SMI Experiment Center provided thirteen files for each participant. There was a single Log File having the extension ".lgf" which included every action taken by the program before and during the experiment in code language. Some of these actions were executing unrecorded test runs, presenting the instructions, starting and stopping the screen recording and running the visuomotor rotation task through Unity.exe. A text file (.txt) provided notes about the time experiment started, deviation scores in x and y axes during calibration phase, and when the experiment ended. Another file (.txt) called "protocol" included mouse clicks with specific coordination which were referred to as "user events". There were three picture files of calibration screen and instructions for calibration and visuomotor rotation task. An EXP File included the description of the experiment, as well as calibration settings such as size and color of the target point. A video clip was among these files with record of every foveal and manual movement made on screen during the experiment. Finally, four Extensible Markup Language files (.xml) contained the sets of rules for encoding all of the files stated above. The preparation and the extraction of the foveal and manual data obtained via SMI Experiment Center during the six trials were analyzed and visualized with The Behavioral and Gaze Analysis software, SMI BeGaze™ version 3.4 (SensoMotoric Instruments, Teltow, Germany). BeGaze required all the files provided by the Experiment Center and reported an error if one of them was missing. Thus, it was extremely crucial to keep all the files in the same folder and to preserve them without making any modification.

After BeGaze was started, each participant's experiment folder was uploaded individually. BeGaze divided the experiment into two parts: calibration and events. By "modify experiment" window, a picture of the background in visuomotor rotation task was uploaded as stimulus image. Then, this image was matched with visuomotor rotation trials using "stimulus association" tab and it was saved. Clicking on the "stimulus" opened the scan path for visuomotor rotation task with the identical stimulus image located on the "screen" background. Scan path provided fixation

points, saccades, eye-blinks and mouse clicks that occurred during the trials. The screen was located at the right side of this listed information. Below the screen there was a timeline allowing for switching to particular user events and trials. When a point of interest was clicked on the timeline, it demonstrated the foveal and manual actions taken so far (Figure 7-A). The information of fixation points gathered through scan path was used to determine areas of interest (AOIs). Fifteen AOIs were created for each of fifteen target locations with circles. The locations of the AOIs were also supported by focus map (Figure 7-B) which demonstrates the most focused areas during an event. Based on the pattern observed in scan path and focus maps, limiting AOIs to targets would result in failure to capture all fixations. Since participants did not always fixate directly on the target, but also around the target. Thus, AOI circles were designed to be wider than the target point to cover the surrounding area. "Key performance indicators" tab explained specific information related to each AOI such as first fixation length, average fixation, entry time and fixation count etc. (Figure 7-C). The program made it possible to save AOI data and use it for other participants as well. The foveal and manual data were extracted from BeGaze via "Event statistics" window which included details for first eye fixation on each AOI (targets) and detailed statistics for user events (mouse clicks).

The only information not provided by BeGaze was the continuous movement of the cursor during visuomotor rotation trials. For this information, the video file including screen record was utilized. The time stamps of the screen record were synchronized with the ones in scan path section. Through the video file it was possible to observe specific time points when participants succeeded in reaching the target area.

The obtained data was formed of both foveal and manual actions throughout the experiment, including time of first eye fixation on the target area and time of cursor arrival in target area. This information was utilized for calculating time interval between first eye-fixation on target and target hit (eye-to-shooting latency), time interval between first eye fixation and cursor arrival on target (eye-to-hand latency), time interval between cursor arrival on target and target hit (hand-to-shooting latency), and time interval between first eye fixation on target and first eye fixation on the next target (eye-to-eye latency).
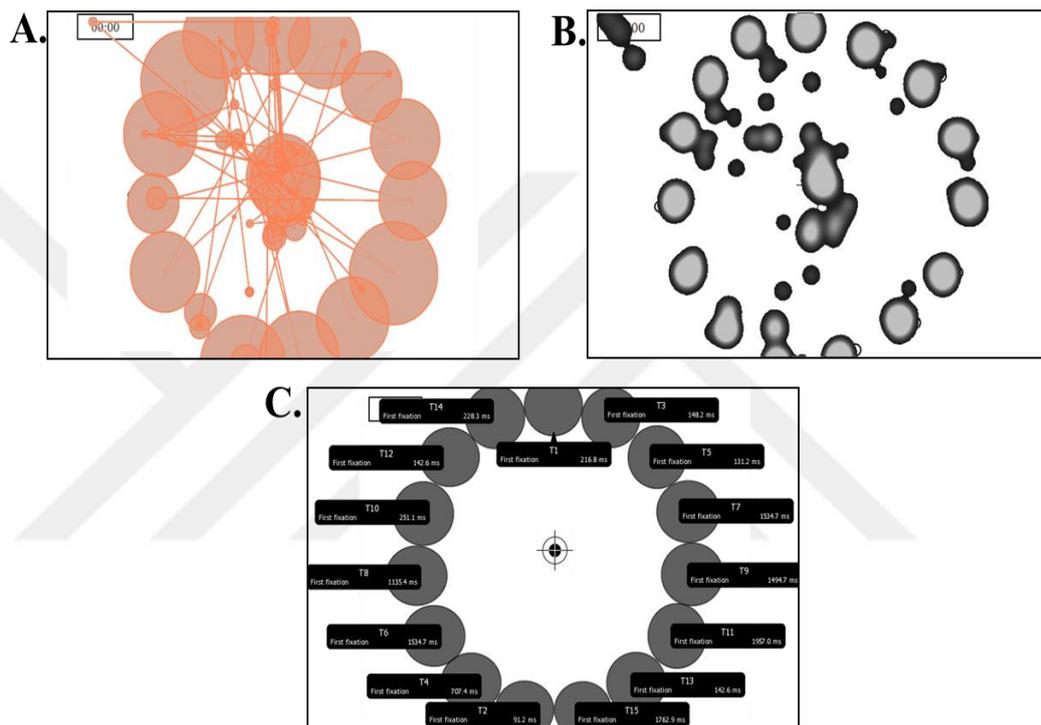
Figure 7. Illustration of data view options in BeGaze (A) scan path demonstrating foveal and manual data (B) focus map demonstrating foveal data (C) areas of interest determined via scan path and focus map

Eye-to-shooting, eye-to-hand, hand-to shooting and eye-to-eye latency allowed for analyzing the local components of eye-hand coordination during adaptation to linear and circular visuomotor rotation tasks. Eye-to-shooting latency provided information related to the relationship between initial foveal activity and movement completion. Eye-to-hand latency was utilized to understand the relationship between initial foveal activity and manual movement directed to the target. Hand-to-shooting latency explained how long it took to complete the movement after target was closely aimed by manual movement. Finally, eye-to-eye latency demonstrated changes in capacity of foveal retina in detecting the next target. Comprehension and analysis related to these parameters were thought to reveal the contribution of local components to global visuomotor adaptation patterns and more specifically, to eye-hand coordination during this process.

2.2. Study 2

2.2.1. Participants

A total of 43 participants with 25 females and 18 males aged between 20 and 50 (M_{age} = 25.23, SE_{age} = 5.94) were included in the study. Participants were formed of lecturers and students of Izmir University of Economics. Prior to beginning, all of the participants read the participants information form and signed the informed consent (Appendix A-B). After having signed the informed consent, they were asked to fill a participant evaluation form (Appendix C). The exclusion criteria for the study included having any neurological or psychological disorder, having experienced head trauma, and having been diagnosed with a cardiovascular disease. In addition to these criteria, non-smoker individuals were chosen for the sample as tobacco usage was stated to have effects on hemoglobin curvature (Nordenberg and Binkin, 1990). All of the participants were asked not to drink coffee 2 hours prior to experiment, since caffeine consumption in a proximate time was revealed to have effect on participants' hemoglobin levels (Heilbronner et al, 2015). Participants' tendencies for hand usage were examined with Edinburgh's Handedness Inventory (Oldfield, 1971) (Appendix D) and as in Study 1; right-handed participants were included in the study. All of them had normal vision or were wearing contact lenses or eyeglasses throughout the experiment. Hence, participants were formed of healthy, non-smoking and right-handed individuals. Participation was again voluntary and no payment was provided. Participants were assigned to either linear or circular

condition coincidentally. Out of 43 participants who were recruited for the study, 7 participants were eliminated owing to saturation or weak signals and 9 of them were excluded owing to too much data loss after raw data was filtered.

2.2.2. Apparatus/Materials/Equipment

The test chamber was sound, warmth and lightproof and whole experiment was recorded with a camera system. Researcher's chamber was located next to the test chamber. The researcher was able to observe the participant through a tinted window during the whole study. In the test chamber there was a comfortable seat and on the armrests of the seat a wooden prop was placed. The wooden prop was utilized for controlling the computer mouse. A monitor was located in front of the participant using an iron tube attached to one the side of the participants' seat. The iron tube was arranged in such a way that the monitor was aligned with participants' heads. Next to the participants' seat, there was an end table on which sensor pad of a 16-channels ƒNIR 200A Model 1200 (fNIR Devices LLC, Photomac MD; www.fnirdevices.com) and ƒNIR control box unit (1100 series) were carefully placed. Hemodynamic response changes in participants' prefrontal cortex were recorded throughout the experiment via CobiStudio software (Drexel University). CobiStudio was installed on a computer in the researcher's chamber. The sensor pad was connected to ƒNIR control box unit using sensor cables. Sensor cables were designed for two sides of the sensor pad, right and left. The computer with CobiStudio was connected to ƒNIR control box unit via a USB cable. Unity (Unity Technologies. Unity 3d. http://unity3d.com/) was used to present visuomotor rotation tasks, record behavioral responses and send markers.

2.2.3. Procedure

Participants were briefly informed about the procedure of the study. They were given the informed consent and asked to sign if they agreed to participate. They were reminded that participation was voluntary and that they could leave whenever they desired. Participants were handed the demographic information form and their answers were assessed based on elimination criteria. Provided that they did not possess any of the characteristics included as elimination criteria, they were given Edinburgh Handedness Inventory. Following this, arrangements were made for the

participant to seat at the chair comfortably. Wooden prop was placed on the armrests and computer mouse was located on the wooden prop.

Participants were given a hairband to wear so that their hair was maintained behind the forehead and did not interfere with the quality of signals. The forehead was cleaned using a make-up remover solution. The solution was dried with a cotton wool so that dirt, sweat or make-up products did not disrupt signals obtained via photoreceptors. Following this process, the sensor pad was placed on participants' forehead based on the instructions in the *f*NIR Imager & CobiStudio manual provided by *f*NIR Devices, L. L. C. (2013). The sensor pad was left neither too tight around the forehead, nor very loose. Applying the sensor pad too tight would limit blood circulation and too loose would leave a weak contact with the forehead. The sensor pad was placed in such a way that the line at the middle of the pad coincided with the middle of the forehead. Eyebrows were used as reference points in this procedure. It was made sure that the connector edge "1" was on the left side of the forehead and the initial "R" was on the right, the initial "L" was on the left. The cables of the sensor pad were removed from participants' vision by moving them over the back of their head. A bonnet was then placed covering the head, specifically the sensor pad so that external light did not intervene with photoreceptors (Figure 8). All the lights in test chamber and researcher's chamber were turned off during data acquisition. Throughout the experiment, the room temperature was kept as 16°C to prevent participants' forehead from sweating. Participants were cautioned to keep their heads as stable as possible to avoid noise caused by head movement.

After the environment of test chamber was settled and participants were ready, CobiStudio software was started to examine the signals obtained from channels for saturation or irregularities. In the program, there was a Layout area demonstrating signals obtained from 16 channels. These channels represented the 16 Channels on the *f*NIR sensor pad. CobiStudio manual suggests that the signals observed in Layout area should not exceed 4000 or remain below 400 for obtaining good quality signal. Different positions, the outline of the skull in forehead area and skin color might require some changes in parameters like LED drive current and initial gain. LED current is suggested to remain between 5mA to 20mA, while initial gain should be set as among the following; 1, 5, 10, 15 and 20. "Start current device" button provided the opportunity to see whether the signals in channels were maintained

Figure 8. Experimental Setup for Study 2. *f*NIR 200A Model 1200 (left) and experimental equipment in test chamber (right)

between 400 and 4000 without recording. If these criteria were not met, the sensor pad on participants' head was examined again for any hair interference or perspiration on the forehead. This procedure was repeated only until the obtained signals became neat and decent. Provided that the criteria stated above were met, "Start New Experiment" button was clicked to create the experiment. Through this window, initials of the experimenter, experimental condition and optional description of the experiment were introduced to the program. Baseline measurement was taken from the participants before presenting the visuomotor rotation task. The time length of the baseline was set as the default length determined by CobiStudio as 10 seconds. The beginning and ending of baseline was demonstrated by the program on the message pane. Following the baseline, "Record" button was clicked and the visuomotor rotation task was opened via Unity and presented on the monitor in the test chamber.

2.2.3.1. Visuomotor Rotation Task

The visuomotor rotation task in Study 2 was identical to the one used in Study 1. Participants were presented with six trials (one baseline trial + five visuomotor rotation trials) in the experiment. They were also randomly assigned to either linear visuomotor rotation condition or circular visuomotor rotation condition. The conditions had the same trajectory manipulations as described in Study 1.

The only alteration made in the second study was related to the resting period. The resting period between trials were used as local baseline measurements for each trial and this resting period varying between ten seconds to fifteen seconds in *f*NIR studies (Sela et al., 2011, 2012), was specified as fifteen seconds in this study. After participants completed all of the trials, the timer stopped for the last trial (Figure 9).

2.2.4. Data Acquisition

Throughout the experiment, hemodynamic responses in participants' prefrontal cortex were recorded via CobiStudio. The signals came from 16-Channels representing the light detectors located on the sensor pad. During data acquisition CobiStudio provided the researcher with the opportunity to observe the changes in the signals simultaneously and to make an overall evaluation of the process. If any of the signals in channels exceeded 4000 or fell below 400, this incident was noted. All of the participants' experimental condition, gender, age and signal quality
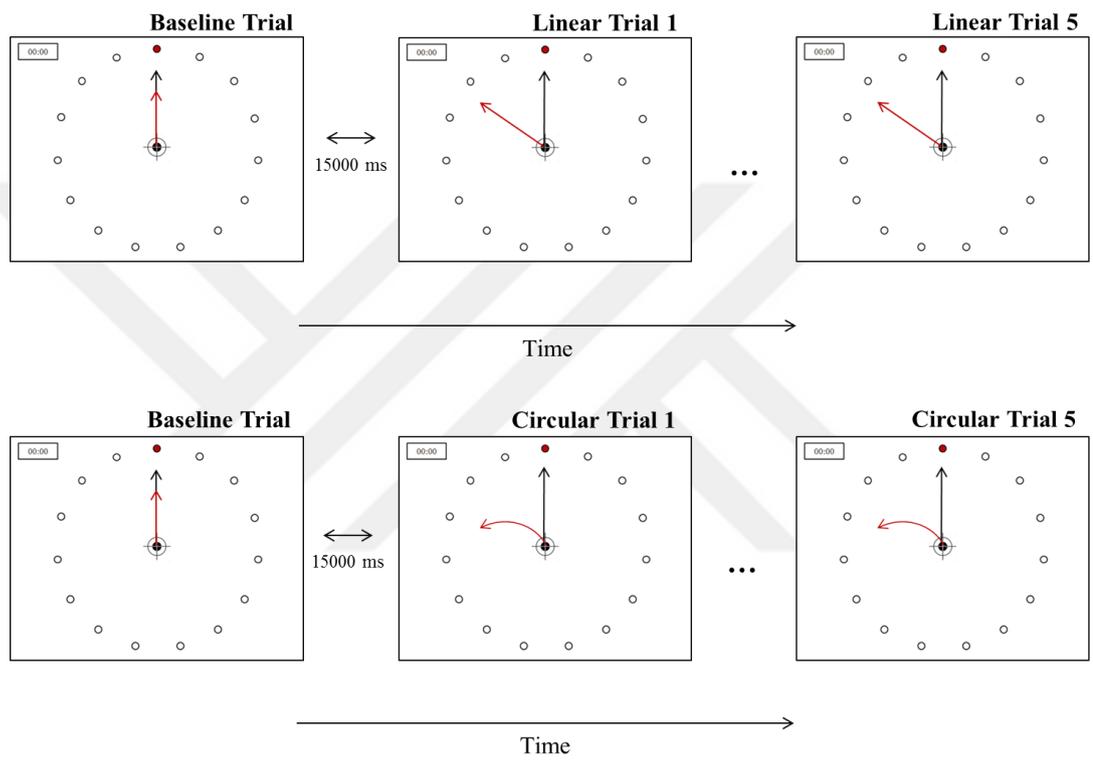
Figure 9. Flow diagram of linear visuomotor rotation task (top) and circular visuomotor rotation task (bottom)

information were gathered in an excel file which provided guidance during data analysis. The time participants took to complete each trial was included as behavioral data of the experiment. Trial completion time of six trials (baseline and rotated) were recorded by Unity for both of the experimental conditions. Markers were sent from Unity to CobiStudio via a virtual port at the beginning and ending of each trial, which allowed for determining the baseline and trial blocks.

2.2.5. Data Preparation

2.2.5.1. Preparing Behavioral Data for Analysis

The length of time spent to complete each trial during visuomotor rotation task was obtained via Unity in a text-file. Then, it was extracted to an excel file and transformed into long data format, with participant ID, consecutive trials, experimental condition and trial completion length on columns and each participant on rows.

2.2.5.2. Preparing NIRS Data for Analysis

CobiStudio, which was used to obtain NIRS data, took two measurements at each second throughout the experiment. These measurements were oxy-Hb (HBO) and deoxy-Hb (HBR) throughout trials. CobiStudio provided four files of the measurement process. Firstly, there was a file with ".nir" extension, labeled as "fnirSoft Light File". The light file is formed of signals obtained through photodetectors and the neural data is in light format. Second file has the extension of ".oxy" and provides oxygenation data throughout the measurements, referred to as "fnirSoft Oxygenation File". The program also provided a marker file including every marker received during the study with ".mrk" extension. Lastly, there was a document file with ".log" extension including date and time of the measurement, ID of the experimenter, ID of the subject, experimental condition and comments written, if any, after the measurement stopped.

The Light File was uploaded to *f*NIR Soft Pro along with the marker file. Prior to conducting any analysis with the data, FIR Filtering was applied to eliminate high frequency noise, effects of respiration and cardiac cycle. Following FIR Filtering, Sliding-window Motion Artifact Rejection (SMAR) was used for minimizing the probable effects of noise caused by head movements (Figure 10). With the aid of marker file, each trial and each local baseline (resting period) measurement were
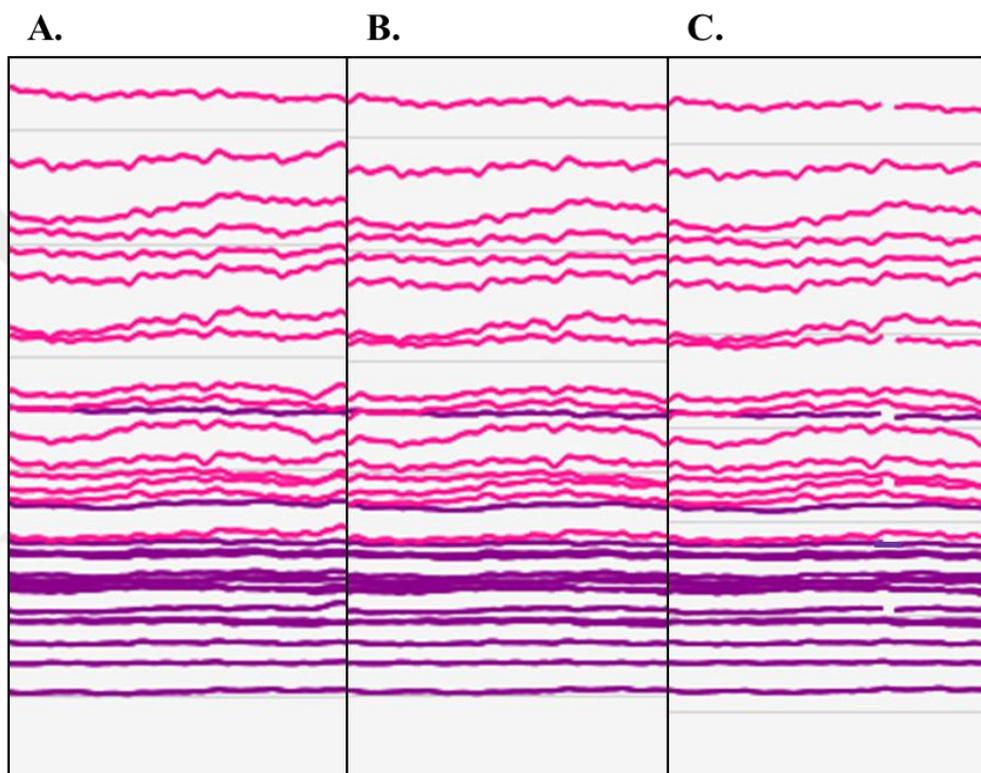
Figure 10. Illustration of data filtering process via *f*NIR Soft Pro (A) raw neural data (B) NIRS data filtering (C) application of SMAR

defined as blocks using Automation tool. There were twelve blocks formed of six trial measurements (baseline and rotated) and six resting period measurements. Following this, all blocks and baseline measurements were saved using "Save Lightgraph Data" window. Hemodynamic changes for 16 channels throughout consecutive trials were calculated with Modified Beer Lambert Law (MBLL). Input variables consisted of measurements taken during visuomotor rotation trials and baseline variables consisted of measurements taken during resting periods. Through the MBLL tool changes in changes in hemodynamic response in each block were calculated for oxy-Hb and deoxy-Hb concentration. The data was extracted from *f*NIR Soft Pro into an excel file, which was then turned into a csv file. In the file similar with the behavioral data, participant ID, consecutive trials, experimental condition and 16 channels were placed on columns and participants on rows. The csv file was then uploaded to RStudio for further analysis.

NIRS data, therefore, allowed for analyzing oxy-Hb and deoxy-Hb concentration obtained from participants' prefrontal cortex during they completed linear and circular visuomotor rotation tasks throughout five consecutive trials.

CHAPTER III

Results

3.1. Data Analysis

The overall data of Study 1 and Study 2 including behavioral data of the two studies, foveal and manual data gathered through Eye-Tracking device and hemodynamic responses obtained via ƒNIR device include repeated measurements taken from participants throughout five consecutive visuomotor rotation trials, meaning that at multiple time points. This type of data is referred to as time course data. Since the source of information in time course data is obtained from same participants in different conditions and at multiple time points, it can also be called nested data. Even if these multiple measurements are uncorrelated between two participants, the measurements that were taken from one participant will tend to be correlated as the source remains the same (Mirman, 2014). In this study, the data are nested at individual participant level and grouped by type of experimental condition participants were assigned to. And as the multiple points in this study are five visuomotor rotation trials completed by each participant, the trials are nested within participants. Generally repeated measures data or longitudinal data, specifically if it is a mixed design, is analyzed with Mixed Design ANOVA or Multilevel Mixed Model Analysis (e.g. Chiodi, 2013; Baldwin and Hoffmann, 2002; Grimm et al., 2011; Brooks and Meltzoff, 2008). Both of the analysis types stated above provide information about the statistical difference between experimental conditions (between-subject variable) and statistical change related to consecutive trials (within-subject variable). Multilevel Mixed Model Analysis which has been frequently used during the recent years has some advantages over Mixed Design ANOVA in analyzing longitudinal data structures (Field et al., 2012). First of all, it does not require assumptions such as homogeneity of regression slopes and independence as it treats longitudinal data as nested data, involving multiple measurements from the same participant. Moreover, while ANOVA demands additional techniques to deal with missing data, in Multilevel Mixed Models parameters are estimated with the

available data and eliminates the need for making imputations to constitute for the missing data.

Multilevel Mixed Models provide various methods for longitudinal data analysis; however curvatures resulting from assessments at multiple time points are thought to be better captured by Growth Curve Analysis (GCA). Growth Curve Analysis specifically has some advantages over traditional analyses like *t*-tests or ANOVA (Mirman, 2014). One of them is that t-tests and ANOVAs treat time measurements as uncorrelated time bins (trial blocks), and as both methods calculate and use mean for analysis, time bins will only have small amount of data and will require more data points. Moreover, considering time points as time bins will turn them into discontinuous measurements, which will make it difficult to observe gradual changes. Lastly, traditional tests tend to ignore individual differences and treat them as members of the same population, by not allowing different intercepts for each participant. On the other hand, Growth Curve Analysis treats time as a continuous variable and provides the opportunity to investigate gradual changes in time course data. It also takes individual differences into account by allowing random intercepts for each participant. Based on the statements made above, behavioral, foveal and manual and neural data gathered in this study was analyzed using Growth Curve Analysis, both to capture individual differences in visuomotor rotation trials and to investigate the gradual change resulting from presenting these consecutive trials.

Before continuing with the analysis, it might be logical to explain some model parameters related to Growth Curve Analysis. Most basic one of these parameters is the intercept, which stands for the initial status of dependent variable at the beginning of measurements (Curran et al., 2010). The changes in pattern throughout measurements are referred to as time terms. When change over time is linear, in other words, the change in dependent variables during measurements at multiple time points either decreases or increases in a linear pattern, adding a single linear term to model is considered as sufficient (Meredith and Tisak, 1990). When change over time is nonlinear, then it would be wise to consider other time terms such as quadratic, cubic, quartic and so on (Urie, 1981). Quadratic time term captures at least one inflection point in the pattern, meaning that there is a change in direction of the curve. Cubic time term, on the other hand, captures two changes in the direction of

the pattern throughout measurements (Grimm et al., 2011). In cases when there is a significant interaction between experimental condition and time terms, for example with cubic term, it explains how condition modulated this cubic pattern in time course of measurements.

The individual time terms tend to be correlated when there are higher order polynomials in the analysis. More clearly; when the quadratic term increases linear term will increase too. Moreover, genuine statistical significance in a higher-order polynomial, such as cubic term, might result in an unreal significance in lower-order polynomial like linear or quadratic terms. Both problems related to collinearity explained above occur since time terms are applied on the same data. In such cases fitting orthogonal polynomials to data is a logical solution because it prevents collinearity between time terms. Therefore, while analyzing the overall data of the present study orthogonal polynomials were utilized to avoid potential biases. All analyses were carried out in R version 3.2.2 using "lme4" package (version 1.1-12). Figures were created using "ggplot2" package (version 2.2.1). Orthogonal polynomials were fit to data using "poly" function which was available in the "lme4" package. Before deciding which polynomial term was appropriate for the analysis, the data was visualized. If the gradual change followed a linear pattern then linear time term was fit to data, similarly if it followed quadratic or cubic patterns the quadratic or cubic time term was defined.

3.2. Study 1

3.2.1. Behavioral Data Results for Study 1

In order to investigate adaptation processes throughout the trials in linear visuomotor rotation and circular visuomotor rotation conditions, task completion lengths were calculated for each of the participants. Prior to main analysis, an independent t-test was conducted on baseline trial to investigate whether participants' performance differed before they continued to linear or circular visuomotor rotation trials. Results indicated that participants' performance level was similar before they continued with rotated trials of the condition they were assigned to, ($t_{(30)} = -1.638$, $p > .05$). This means that trial completion length was similar for baseline trial in linear ($M = 29.81$, $SE = 1.00$) and circular ($M = 30.07$, $SE = .95$) conditions.

Growth Curve Analysis (Mirman, 2014) was conducted to analyze trial completion length of participants in linear visuomotor rotation condition and circular visuomotor rotation condition and the gradual change of trial completion length throughout five consecutive trials. The overall curves were modeled with linear time term and fixed effect of condition on linear time term as the gradual change occurred in linear pattern. The linear visuomotor rotation condition was treated as the reference category and parameters were estimated for circular visuomotor rotation condition. The model also included random effect of participant on trials. The fixed effect of condition was added individually and its effects on model fit were evaluated using model comparisons. Improvements in model fit were evaluated using -2 times the change in likelihood, which is distributed as χ^2 with degrees of freedom equal to the number of parameters added. Results revealed that the effect of condition on the intercept improved model fit ($\chi^2_{(1)} = 6.37$, $p < .05$). However; the effect of condition on linear term (slope) failed to improve model fit ($\chi^2_{(1)} = 0.26$, $p > .05$), suggesting no interaction between experimental condition and gradual change of trial completion length throughout consecutive trials (Figure 11).

There was a significant random effect for the intercept, (*Estimate* = 44.35, *SE* = 1.76, *p* < .001) indicating that initial performance of participants in visuomotor rotation trials were highly diverse among the sample. Estimate value of linear time term (slope) (*Estimate* = -4.02, *SE* = 0.34, *p* < .001), referring to curvature of trial as a predictor, suggests a negative relationship between trial and trial completion time indicating that as trials progressed the amount of time participants took to complete trials decreased. There was also a significant effect of condition on the intercept, indicating longer trial completion time in circular visuomotor rotation condition with positive estimate value (*Estimate* = 3.53, *SE* = 1.33, *p* < .05) relative to linear visuomotor rotation condition (Table 1).

3.2.2. Foveal and Manual Data Results

Based on the data provided by the Eye-Tracking Device, local components related to eye-motor coordination that contribute to global visuomotor rotation adaptation patterns were examined. The examination was carried out within the scope of linear visuomotor motor rotation and circular visuomotor rotation based on the following local components:
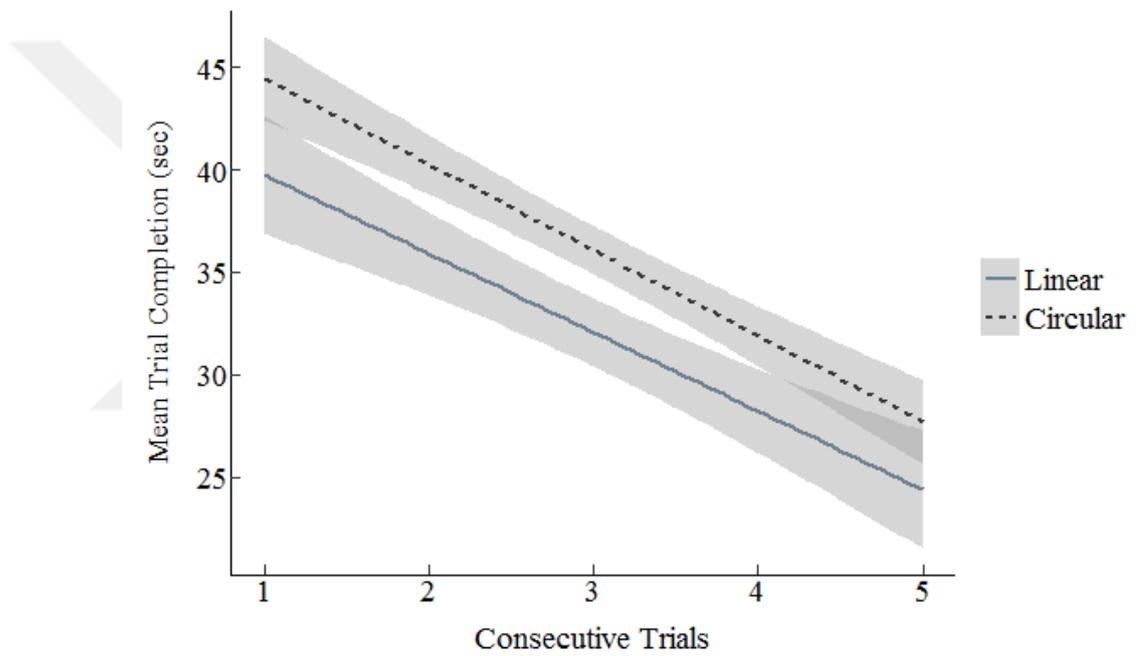
Figure 11. Mean (with 95% CI) trial completion length throughout consecutive trials in linear visuomotor rotation and circular visuomotor rotation conditions in Study 1

Table 1

Parameter Estimates for Analysis of Effect of Condition on Trial Completion Time in Study 1

	Estimate	Std.Error	t	p
Intercept	44.3506	1.7585	25.221	<2e-16***
Linear Term	-4.0156	0.3374	- 11.902	9.55e-15***
Circular: Intercept	3.5300	1.3305	2.653	0.0113*

Signif. Codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "."

1. Time interval between first eye fixation on target and target hit (eye-to-shooting latency)
2. Time interval between first eye fixation on target and arrival of cursor on target (eye-to-hand latency)
3. Time interval between arrival of cursor in target area and target hit (hand-to-shooting latency)
4. Time interval between first eye fixation on target and first eye fixation on the next target (eye-to-eye latency)

In order to investigate whether the level of participants regarding the parameters stated above were similar in baseline trial, independent t-tests were conducted for each of the parameters. The results indicated a non-significant difference in participants' levels in the baseline trial for eye-to-shooting latency, ($t_{(30)} = -1.134$, $p > .05$), eye-to-hand latency, ($t_{(30)} = -1.460$, $p > .05$), hand-to-shooting latency, ($t_{(30)} = -0.144$, $p > .05$), and finally eye-to-eye latency, ($t_{(30)} = -1.7156$, $p > .05$). This findings suggest that eye-to-shooting latency was similar for linear ($M = 1401.94$, $SE = 71.72$) and circular ($M = 1511.44$, $SE = 64.60$) conditions in baseline trial. Also there was a non-significant difference for linear ($M = 441.81$, $SE = 29.02$) and circular ($M = 102.48$, $SE = 25.62$) conditions in baseline trial regarding eye-to-hand latency. Hand-to-shooting latency indicated no difference in baseline trial for linear ($M = 1001.75$, $SE = 61.73$) and circular ($M = 1013.13$, $SE = 49.31$) conditions as well. And finally, eye-to-eye latency was similar in baseline trial for linear ($M = 1856.47$, $SE = 253.37$) and circular ($M = 2006.26$, $SE = 223.98$) visuomotor rotation conditions.

The gradual change regarding local components specified as eye-to-shooting, eye-to-hand, hand-to-shooting and eye-to-eye latency throughout consecutive linear or circular visuomotor rotation trials were investigated separately using Growth Curve Analysis. As it was with the behavioral data, the overall curves were modeled with linear time term (slope) and fixed effect of condition on linear time term, as determined by gradual change pattern of visualized data. Linear visuomotor rotation condition was again treated as reference category and compared with circular visuomotor rotation condition. Again, random effect of participant on trials was included in the model and the fixed effect of condition on model fit was evaluated using -2 times the change in likelihood.

For eye-to-shooting latency; the findings of the analysis suggested that effect of condition on the intercept improved model fit, ($\chi^2_{(1)} = 5.21$, $p < .05$) and the effect of condition on linear time term (slope) did not improve model fit ($\chi^2_{(1)} = 0.30$, $p > .05$), meaning there was no significant interaction between experimental condition and gradual change of trial completion length throughout consecutive trials (Figure 12). The initial eye-to-shooting latency was found to be highly diverse among the participants since there was a significant random effect for the intercept, (*Estimate* = 2.28, *SE* = 0.11, $p < .001$). There was also a significant negative relationship between trial and eye-to-shooting latency inferred from the negative estimate value of the linear term (slope) (*Estimate* = -0.22, *SE* = 0.21, $p < .001$), which demonstrated that as trials progressed, the time interval between first eye fixation on target and target hit decreased in a linear pattern. A significant effect of experimental condition on the intercept was also found with a positive estimate value, suggesting longer eye-to-shooting latency in circular condition (*Estimate* = 0.21, *SE* = 0.09, $p < .05$) than in linear condition. This means that the time interval between first eye-fixation and target hit changed depending on the experimental condition participants were assigned to (Table 2).

The results of analysis conducted for eye-to-hand latency suggested that both the effect of condition on the intercept, ($\chi^2_{(1)} = 1.78$, $p > .05$) and the effect of condition on linear time term (slope) ($\chi^2_{(1)} = 1.77$, $p > .05$) failed to improve model fit. This finding suggested that the time interval between first eye fixation on target and arrival of cursor on target did not differ for linear and circular visuomotor rotation conditions or throughout consecutive trials.

The analysis carried out for hand-to-shooting latency revealed no improvements in model fit for the effect of condition on the intercept, ($\chi^2_{(1)} = 3.10$, $p > .05$) and the effect of condition on linear time term (slope) ($\chi^2_{(1)} = 0.00$, $p > .05$), suggesting that the time interval between arrival of cursor in target area and target hit was similar for linear visuomotor rotation and circular visuomotor rotation conditions and remained without significant changes throughout the trials.

Finally, for eye-to-eye latency; the results of the analysis suggested that the effect of condition on the intercept did improve model fit, ($\chi^2_{(1)} = 6.62$, $p < .05$), however the effect of condition on linear time term (slope) failed to improve model fit ($\chi^2_{(1)} = 0.29$, $p > .05$), indicating a non-significant interaction between
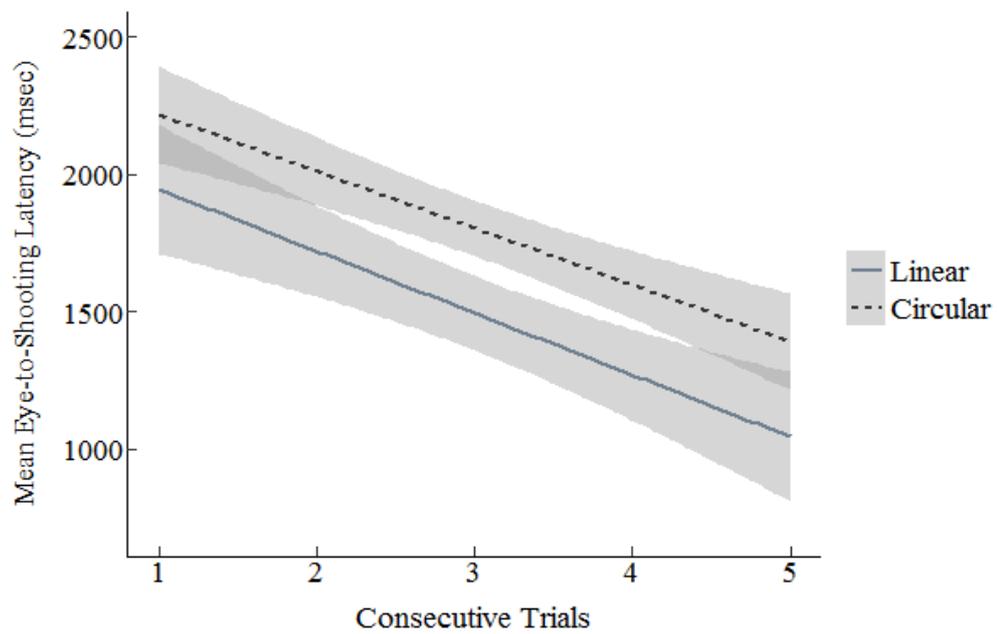
Figure 12. Mean (with 95% CI) eye-to-shooting latency throughout consecutive trials in linear visuomotor rotation and circular visuomotor rotation conditions

Table 2

Parameter Estimates for Analysis of Effect of Condition on Eye-to-Shooting Latency

	Estimate	Std.Error	t	p
Intercept	2138.07	120.62	17.725	<2e-16***
Linear Term	-215.67	29.43	- 7. 329	2.2e-10***
Circular: Intercept	315.52	97.56	3.234	0.00239**

Signif. Codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "."

experimental condition and gradual change of trial completion length throughout consecutive trials (Figure 13). The initial eye-to-eye latency was revealed to be highly diverse among the sample as a significant random effect for the intercept was found, (*Estimate* = 2969.19, *SE* = 118.58, *p* < .001). A significant negative relationship between trial and eye-to-eye latency was revealed based on the negative estimate value of the linear term (slope) (*Estimate* = -270.18, *SE* = 22.94, *p* < .001), which demonstrated that as trials progressed, the time interval between first eye fixation on target and first eye fixation on the next target decreased in a linear pattern. There was a significant effect of experimental condition on the intercept with a positive estimate value, suggesting longer eye-to-eye latency in circular condition (*Estimate* = 245.37, *SE* = 90.41, *p* < .01) than in linear condition. These results suggested that the time interval between first eye-fixation on target and first eye fixation on the next target changed depending on the experimental condition participants were assigned to (Table 3).

3.3. Study 2

3.3.1. Behavioral Data Results for Study 2

Behavioral data of Study 2 is identical with the behavioral data of Study 1, including trial completion length of five consecutive linear visuomotor rotation and circular visuomotor rotation trials. However; as the participants of Study 1 and Study 2 were different, behavioral results were analyzed for Study 2 separately. Before the main analysis of behavioral data of Study 2, the time participants took to complete baseline trial in linear and circular conditions was analyzed with independent t-test in order to investigate whether there was a statistically significant difference in participants' performance prior to rotated trials. Results of the analysis revealed a non-significant difference in baseline trial completion time, ($t_{(24.36)} = 0.22$, *p* > .05) indicating that participants' performance were similar in linear (*M* = 31.37, *SE* = 3.48) and circular (*M* = 31.05, *SE* = 3.78) conditions before they proceeded with visuomotor rotation task.

The behavioral data of Study 2 was also analyzed using Growth Curve Analysis. The fitting of the curves, fixed and random effects structure and model parameters were identical with Study 1. Model fits were again evaluated using -2 times the change in log-likelihood after adding fixed effect of condition and effect of experimental
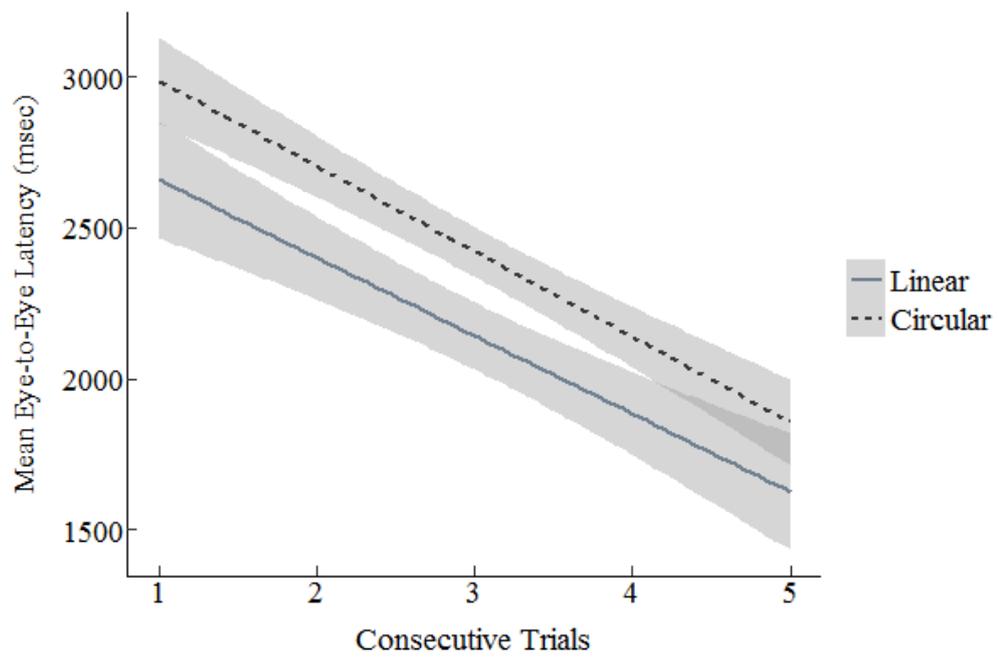
Figure 13. Mean (with 95% CI) eye-to-eye latency throughout consecutive trials in linear visuomotor rotation and circular visuomotor rotation conditions

Table 3

Parameter Estimates for Analysis of Effect of Condition on Eye-to-eye Latency

	Estimate	Std.Error	t	p
Intercept	2969.19	118.58	25.039	<2e-16***
Linear Term	-270.18	22.94	- 11.778	1.11e-14***
Circular: Intercept	245.37	90.41	2.714	0.00974**

Signif. Codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "."

condition on linear time term (slope) individually. Results of the analysis demonstrated that effect of condition on the intercept failed to improve model fit, ($\chi^2_{(1)} = 5.15$, $p > .05$), however; the effect of condition on linear time term (slope) did improve the model fit, ($\chi^2_{(1)} = 6.36$, $p < .05$), indicating significant interaction between experimental condition and gradual change of trial completion length throughout consecutive trials (Figure 14).

There was a significant random effect for the intercept, (*Estimate* = 43.56, *SE* = 2.72, $p < .001$) indicating that initial performance of participants in visuomotor rotation trials were highly diverse among the sample. Estimate value of linear term (slope) (*Estimate* = -4.59, *SE* = 0.47, $p < .001$), referring to curvature of trial as a predictor, suggests a negative relationship between trial and trial completion time indicating that as trials progressed the amount of time participants took to complete trials decreased in a linear pattern. There was also a significant effect of Condition on the linear time term (slope), indicating longer trial completion time in circular visuomotor rotation condition (*Estimate* = 0.77, *SE* = 0.30, $p < .05$) relative to linear visuomotor rotation condition (Table 4).

3.3.2. NIRS Data Results

Prior to conducting any analysis related to oxy-Hb and deoxy-Hb concentration, during consecutive visuomotor rotation trials, overall mean of oxy-Hb and deoxy-Hb was obtained from 16-Channels for baseline trial. Hemodynamic response during baseline trial was compared for linear and circular visuomotor rotations with independent t-test using R. This analysis was conducted on the 16 channels for oxy-Hb and deoxy-Hb levels separately. According to the results of the analysis, the difference in hemodynamic response during baseline trial was non-significant for all of the channels regarding oxy-Hb: in Channel 1, ($t_{(20.15)} = 0.86$, $p > .05$) ($M_{circular} = -0.116898769$, $M_{linear} = -0.003260643$); Channel 2, ($t_{(23.99)} = 1.36$, $p > .05$) ($M_{circular} = -0.08846354$, $M_{linear} = 0.16206985$); Channel 3, ($t_{(24.49)} = 1.44$, $p > .05$) ($M_{circular} = -0.233085154$, $M_{linear} = 0.004485071$); Channel 4, ($t_{(23.10)} = 0.60$, $p > .05$) ($M_{circular} = -0.01168677$, $M_{linear} = 0.09506454$); Channel 5, ($t_{(24.27)} = 2.39$, $p > .05$) ($M_{circular} = -0.44782908$, $M_{linear} = -0.03327543$); Channel 6, ($t_{(24.98)} = 0.92$, $p > .05$) ($M_{circular} = -0.25079323$, $M_{linear} = -0.06101807$); Channel 7, ($t_{(22.83)} = 1.71$, $p > .05$) ($M_{circular} = -0.5574732$, $M_{linear} = -0.1026566$); Channel 8, ($t_{(17.03)} = 1.59$, $p > .05$) ($M_{circular} = -0.43083800$, $M_{linear} = -0.02931157$); Channel 9, ($t_{(23.69)} = 2.29$, $p > .05$)
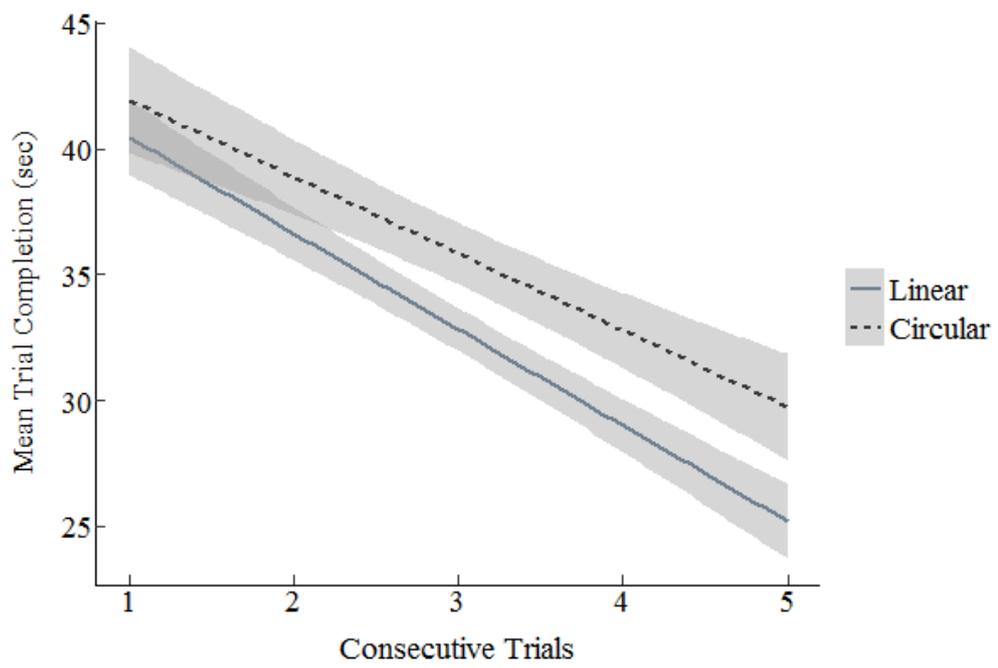
Figure 14. Mean (with 95% CI) trial completion length throughout consecutive trials in linear visuomotor rotation and circular visuomotor rotation conditions in Study 2

Table 4

Parameter Estimates for Analysis of Effect of Condition on Trial Completion Time in Study 2

	Estimate	Std.Error	t	p
Intercept	43.5633	2.7208	16.011	<2e-16***
Circular: Intercept	0.7128	1.7580	0.405	0.6870
Linear Term	-4.5876	0.4669	- 9.825	<2e-16***
Circular: Linear Term	0.7690	0.3017	2.549	0.0118*

Signif. Codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "."

(M_{circular} = -0.57365785, M_{linear} = -0.06588571); Channel 10, ($t_{(19.59)}$ = 1.96, p > .05)

(M_{circular} = -0.55126200, M_{linear} = -0.07262793); Channel 11, ($t_{(22.35)}$ = 2.75, p > .05)

(M_{circular} = -0.43638075, M_{linear} = 0.05727386); Channel 12, ($t_{(23.45)}$ = 1.68, p > .05)

(M_{circular} = -0.26594692, M_{linear} = 0.07087792); Channel 13, ($t_{(21.04)}$ = 2.01, p > .05)

(M_{circular} = -0.29592709, M_{linear} = 0.05737185); Channel 14, ($t_{(22.84)}$ = 1.88, p > .05)

(M_{circular} = -0.1627417, M_{linear} = 0.1709245); Channel 15, ($t_{(21.55)}$ = 1.43, p > .05)

(M_{circular} = -0.22467373, M_{linear} = 0.03922054); and Channel 16, ($t_{(20.04)}$ = 1.74, p > .05) (M_{circular} = -0.1650352, M_{linear} = 0.2399921).

The results for deoxy-Hb revealed that the difference in hemodynamic response during baseline trial was non-significant for all of the channels regarding deoxy-Hb: in Channel 1, ($t_{(17.39)}$ = -1.34, p > .05) (M_{circular} = 0.15381277, M_{linear} = -0.01663936); Channel 2, ($t_{(22.13)}$ = -0.67, p > .05) (M_{circular} = -0.04034954, M_{linear} = -0.01663936); Channel 3, ($t_{(23.13)}$ = -1.23, p > .05) (M_{circular} = 0.13381123, M_{linear} = -0.03062457); Channel 4, ($t_{(22.11)}$ = -2.04, p > .05) (M_{circular} = 0.1530594, M_{linear} = -0.1346594); Channel 5, ($t_{(23.95)}$ = -1.47, p > .05) (M_{circular} = 0.08301392, M_{linear} = -0.10852207); Channel 6, ($t_{(24.87)}$ =-1.62, p > .05) (M_{circular} = 0.14946085, M_{linear} = -0.05800536); Channel 7, ($t_{(21.77)}$ = -0.54, p > .05) (M_{circular} = -0.003297154, M_{linear} = -0.064212857); Channel 8, ($t_{(16.58)}$ = 0.31, p > .05) (M_{circular} = 0.06594425, M_{linear} = 0.11215036); Channel 9, ($t_{(19.61)}$ = -0.11, p > .05) (M_{circular} = 0.03114600, M_{linear} = 0.01712364); Channel 10, ($t_{(22.17)}$ = 0.53, p > .05) (M_{circular} = -0.0895440, M_{linear} = -0.0016175); Channel 11, ($t_{(20.31)}$ = -1.32, p > .05) (M_{circular} = 0.19738225, M_{linear} = 0.01741521); Channel 12, ($t_{(23.99)}$ = -1.20, p > .05) (M_{circular} = 0.18509369, M_{linear} = 0.05728023); Channel 13, ($t_{(18.66)}$ = -1.24, p > .05) (M_{circular} = 0.098263000, M_{linear} = -0.007483615); Channel 14, ($t_{(19.67)}$ = -1.23, p > .05) (M_{circular} = 0.09481117, M_{linear} = -0.02410208); Channel 15, ($t_{(18.22)}$ = 0.16, p > .05) (M_{circular} = -0.01292018, M_{linear} = 0.01056846); and Channel 16, ($t_{(18.03)}$ = 0.87, p > .05) (M_{circular} = -0.2666709, M_{linear} = -0.1292628).

Growth Curve Analysis was used to analyze hemodynamic changes in prefrontal cortex during five consecutive trials of linear visuomotor rotation and circular visuomotor rotation. Hemodynamic change curves were modeled with a third-order (cubic) orthogonal polynomial model for each of the 16-Channels and fixed effect of condition on all time terms: linear, quadratic and cubic. During the analysis, linear visuomotor rotation condition was treated as the reference category

and parameters were estimated for circular visuomotor rotation condition, as in behavioral data analysis. The model also included random effects of participants in consecutive trials on all time terms and participant-by-condition random effects on all time terms except the cubic term. Cubic term was removed to avoid overparameterization and as removal of a parameter is conducted iteratively, highest-order interaction term was removed, provided that no significant loss of goodness of fit in likelihood ratio tests (Bates et al., 2015). Similar with behavioral analysis, fixed effect of condition was added individually and effect of experimental condition on model fit was evaluated using model comparisons. Again, improvements in model fit were evaluated using -2 times the change in log-likelihood. The model mentioned above was conducted separately for oxy-Hb and deoxy-Hb. Since oxy-Hb and deoxy-Hb contain signals obtained from 16 Channels and all of these signals were taken from one participant as dependent variable measurements; false discovery rate corrections with q determined as .05 were applied to significance values obtained from model fit evaluations to avoid family-wise error (Benjamini and Hochberg, 1995).

3.3.2.1. Oxy-Hb

Results revealed that effect of condition on the intercept did not improve model fit for all of the 16-Channels regarding oxy-Hb concentration: Channel 1, ($\chi^2_{(1)} = 2.55$, $p > .05$); Channel 2, ($\chi^2_{(1)} = 0.25$, $p > .05$); Channel 3, ($\chi^2_{(1)} = 1.84$, $p > .05$); Channel 5, ($\chi^2_{(1)} = 2.61$, $p > .05$); Channel 7, ($\chi^2_{(1)} = 0.53$, $p > .05$); Channel 8, ($\chi^2_{(1)} = 0.76$, $p > .05$); Channel 9, ($\chi^2_{(1)} = 1.41$, $p > .05$); Channel 10, ($\chi^2_{(1)} = 0.37$, $p > .05$); Channel 11, ($\chi^2_{(1)} = 3.47$, $p > .05$); Channel 12, ($\chi^2_{(1)} = 1.75$, $p > .05$); Channel 13, ($\chi^2_{(1)} = 1.34$, $p > .05$); Channel 14, ($\chi^2_{(1)} = 1.08$, $p > .05$); Channel 15, ($\chi^2_{(1)} = 0.42$, $p > .05$); and Channel 16, ($\chi^2_{(1)} = 0.31$, $p > .05$). Despite the initial analysis indicated a significant effect of condition on the intercept; this effect was lost in Channel 4, ($\chi^2_{(1)} = 4.04$, $p > .05$) and Channel 6, ($\chi^2_{(1)} = 4.87$, $p > .05$) after applying false discovery rate corrections.

However; the effect of condition on cubic time term (slope) did improve the model fit in some of the Channels indicating significant interaction between experimental condition and gradual change in oxy-Hb concentration throughout trials: Channel 2, ($\chi^2_{(3)} = 89.10$, $p < .05$); Channel 3, ($\chi^2_{(3)} = 52.69$, $p < .05$); Channel 5, ($\chi^2_{(3)} = 23.10$, $p < .05$); Channel 6, ($\chi^2_{(3)} = 43.91$, $p < .05$); Channel 7, ($\chi^2_{(3)} =$

53.36, $p < .05$); Channel 9, ($\chi^2_{(3)} = 109.98$, $p < .05$); Channel 10, ($\chi^2_{(3)} = 54.96$, $p < .05$); Channel 11, ($\chi^2_{(3)} = 49.44$, $p < .05$); Channel 12, ($\chi^2_{(3)} = 33.03$, $p < .05$); Channel 13, ($\chi^2_{(3)} = 27.51$, $p < .05$); Channel 14, ($\chi^2_{(3)} = 11.05$, $p < .05$); Channel 15, ($\chi^2_{(3)} = 115.10$, $p < .05$) and Channel 16, ($\chi^2_{(3)} = 169.62$, $p < .05$) and failed to improve model fit in Channel 1, ($\chi^2_{(3)} = 5.98$, $p > .05$); Channel 4, ($\chi^2_{(3)} = 0.12$, $p > .05$) and Channel 8, ($\chi^2_{(3)} = 0.33$, $p > .05$).

There was a significant random effect for the intercept in Channel 7, (*Estimate* = 0.14620, *SE* = 0.06565, $p < .05$) and Channel 10, (*Estimate* = 0.17310, *SE* = 0.07737, $p < .05$), indicating that initial level of oxy-Hb during visuomotor rotation trials were highly diverse among the sample. The parameter estimates for the Channels in which the effect of condition on cubic term improved model fit can be seen in Table 5.

There was also a significant effect of experimental condition on the cubic term (slope) in the following Channels: Channel 2, (*Estimate* = 0.18128, *SE* = 0.01917, $p < .001$); Channel 3, (*Estimate* = 0.11790, *SE* = 0.01646, $p < .001$); Channel 5, (*Estimate* = 0.07275, *SE* = 0.01517, $p < .001$); Channel 6, (*Estimate* = 0.11750, *SE* = 0.01848, $p < .001$); Channel 7, (*Estimate* = 0.12250, *SE* = 0.01707, $p < .001$); Channel 9, (*Estimate* = 0.18450, *SE* = 0.01757, $p < .001$); Channel 10, (*Estimate* = 0.14160, *SE* = 0.01907, $p < .001$); Channel 11, (*Estimate* = 0.11791, *SE* = 0.01686, $p < .001$); Channel 12, (*Estimate* = 0.10850, *SE* = 0.01935, $p < .001$); Channel 13, (*Estimate* = 0.09671, *SE* = 0.01843, $p < .001$); Channel 14, (*Estimate* = -0.05263, *SE* = 0.02102, $p < .05$); Channel 15, (*Estimate* = 0.16323, *SE* = 0.01518, $p < .001$); and Channel 16, (*Estimate* = 0.25580, *SE* = 0.01964, $p < .001$).

In all of the Channels given above, except Channel 14, positive estimate value for the effect of experimental condition on the cubic term suggests a shallower curvature in linear condition than in circular condition. This means that; as trials progressed oxy-Hb concentration in circular visuomotor rotation condition was higher than linear visuomotor rotation condition. The exception of Channel 14 might be as a result of the effect of experimental condition is significant on quadratic time term too. And while the estimate value of the cubic term in Channel 14 suggests that circular visuomotor rotation task caused lower oxy-Hb concentration, quadratic term suggests the opposite, (*Estimate* = 0.30090, *SE* = 0.13450, $p < .05$).

Table 5

Parameter Estimates for Analysis of Effect of Condition on Oxygenated Hemoglobin

	Estimate	Std.Error	t	p
Channel 2				
Intercept	-0.01009	0.09061	-0.111	0.912
Linear	0.02250	0.11158	0.202	0.842
Quadratic	0.02074	0.10962	0.189	0.851
Cubic	-0.26471	0.01385	-19.113	<2e-16***
Circular: Intercept	0.06319	0.12813	0.493	0.626
Circular: Linear	0.04567	0.15776	0.289	0.775
Circular: Quadratic	0.11983	0.15498	0.773	0.446
Circular: Cubic	0.18128	0.01917	9.457	<2e-16***
Channel 3				
Intercept	0.06676	0.05596	1.193	0.243
Linear	-0.05531	0.09821	-0.563	0.578
Quadratic	0.00084	0.07573	0.011	0.991
Cubic	-0.23020	0.01164	-19.764	<2e-16***
Circular: Intercept	0.12360	0.08063	1.533	0.137
Circular: Linear	0.09231	0.14150	0.652	0.520
Circular: Quadratic	-0.09212	0.10910	-0.844	0.406
Circular: Cubic	0.11790	0.01646	7.159	8.67e-13***
Channel 5				
Intercept	0.08213	0.06350	1.293	0.243
Linear	-0.01694	0.06751	-0.251	0.578
Quadratic	0.06924	0.08735	0.793	0.991
Cubic	-0.13130	0.01080	-12.060	<2e-16***
Circular: Intercept	0.15380	0.09151	1.681	0.137
Circular: Linear	0.06602	0.09726	0.679	0.520
Circular: Quadratic	-0.04316	0.12580	-0.343	0.406
Circular: Cubic	0.07275	0.01517	4.795	1.65e-06***

	Estimate	Std.Error	t	p
Channel 6				
Intercept	0.04449	0.06105	0.729	0.472
Linear	0.11450	0.07587	1.509	0.143
Quadratic	0.02121	0.08383	0.253	0.802
Cubic	-0.14280	0.01313	-10.875	<2e-16***
Circular: Intercept	0.13330	0.08796	1.515	0.141
Circular: Linear	-0.18270	0.10930	-1.672	0.106
Circular: Quadratic	0.13540	0.12070	1.122	0.272
Circular: Cubic	0.11750	0.01848	6.360	2.1e-10***
Channel 7				
Intercept	0.14620	0.06565	2.227	0.0344*
Linear	-0.08260	0.04888	-1.690	0.1025
Quadratic	0.06084	0.08313	0.732	0.4706
Cubic	-0.11910	0.01213	-9.818	<2e-16***
Circular: Intercept	0.09724	0.09459	1.028	0.3131
Circular: Linear	0.09491	0.07038	-1.349	0.1887
Circular: Quadratic	0.07739	0.11980	1.646	0.5236
Circular: Cubic	0.12250	0.01707	7.177	7.6e-13***
Channel 9				
Intercept	0.12430	0.07398	1.680	0.104
Linear	-0.06572	0.05644	-1.164	0.254
Quadratic	0.09474	0.08656	1.095	0.283
Cubic	-0.19770	0.01246	-15.870	<2e-16***
Circular: Intercept	0.14410	0.01066	1.352	0.188
Circular: Linear	0.03093	0.08128	0.381	0.706
Circular: Quadratic	0.06098	0.12470	0.489	0.629
Circular: Cubic	0.18450	0.01757	10.502	<2e-16***

	Estimate	Std.Error	t	p
Channel 10				
Intercept	0.17310	0.07737	2.237	0.034*
Linear	-0.09134	0.06189	-1.476	0.152
Quadratic	0.11960	0.08047	1.487	0.149
Cubic	-0.26150	0.01321	-19.795	<2e-16***
Circular: Intercept	0.06017	0.11390	0.528	0.602
Circular: Linear	-0.01573	0.09105	-0.173	0.864
Circular: Quadratic	-0.00410	0.11840	-0.042	0.967
Circular: Cubic	0.14160	0.01907	7.421	1.26e-13***
Channel 11				
Intercept	0.09041	0.07751	1.166	0.254
Linear	-0.02617	0.06764	-0.387	0.702
Quadratic	0.10716	0.06688	1.602	0.121
Cubic	-0.19101	0.01173	-16.286	<2e-16***
Circular: Intercept	0.17926	0.11408	1.571	0.128
Circular: Linear	-0.07837	0.09951	-0.788	0.438
Circular: Quadratic	0.03105	0.09838	0.316	0.755
Circular: Cubic	0.11791	0.01686	6.994	2.85e-12***
Channel 12				
Intercept	0.13264	0.07197	1.843	0.0768
Linear	0.05873	0.07821	0.751	0.4594
Quadratic	0.02977	0.10703	0.278	0.7831
Cubic	-0.20170	0.01396	-14.453	<2e-16***
Circular: Intercept	0.09053	0.10177	0.889	0.3819
Circular: Linear	-0.13969	0.11056	-1.263	0.2176
Circular: Quadratic	0.04913	0.15133	0.325	0.7480
Circular: Cubic	0.10850	0.01935	5.608	2.1e-08***

	Estimate	Std.Error	t	p
Channel 13				
Intercept	0.05858	0.07208	0.813	0.424
Linear	-0.06847	0.10770	-0.636	0.531
Quadratic	0.08499	0.06943	1.224	0.233
Cubic	-0.19110	0.01266	-15.090	<2e-16***
Circular: Intercept	0.12090	0.10650	1.136	0.267
Circular: Linear	-0.00022	0.15900	-0.001	0.999
Circular: Quadratic	-0.00091	0.10250	0.009	0.993
Circular: Cubic	0.09671	0.01843	5.248	1.58e-07***
Channel 14				
Intercept	0.03670	0.05712	0.642	0.5264
Linear	0.00442	0.11360	0.032	0.9751
Quadratic	-0.03282	0.09326	-0.352	0.7278
Cubic	-0.13710	0.01486	-9.229	<2e-16***
Circular: Intercept	0.03380	0.08242	0.410	0.6853
Circular: Linear	-0.00239	0.18990	-0.013	0.9901
Circular: Quadratic	0.30090	0.13450	2.236	0.0345*
Circular: Cubic	-0.05263	0.02102	-2.503	0.0123*
Channel 15				
Intercept	-0.04717	0.04509	-1.046	0.306
Linear	-0.10417	0.06847	-1.521	0.141
Quadratic	0.07777	0.09508	0.818	0.421
Cubic	-0.16890	0.01053	-16.048	<2e-16***
Circular: Intercept	0.02990	0.06659	0.449	0.657
Circular: Linear	-0.04078	0.10109	-0.403	0.690
Circular: Quadratic	0.12990	0.14040	0.925	0.364
Circular: Cubic	0.16323	0.01518	-10.753	<2e-16***

	Estimate	Std.Error	t	p
Channel 16				
Intercept	-0.06983	0.05979	-1.168	0.254
Linear	-0.05577	0.09921	-0.562	0.579
Quadratic	-0.09001	0.12830	-0.702	0.489
Cubic	-0.18590	0.01415	-13.136	<2e-16***
Circular: Intercept	0.04192	0.08454	0.496	0.625
Circular: Linear	0.00779	0.14030	0.056	0.956
Circular: Quadratic	0.21920	0.18130	1.209	0.239
Circular: Cubic	0.25580	0.01964	13.020	<2e-16***

Signif. Codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "."

The significant interaction effect between experimental condition and cubic term (slope) regarding oxy-Hb concentration was visualized. It can be seen in that in Channel 2, Channel 3, Channel 5, Channel 10, Channel 11, Channel 12, Channel 13, Channel 14 and Channel 16, oxy-Hb in both linear and circular conditions changed throughout the trials in a cubic pattern (Figure 15-23). In all of these Channels, oxy-Hb concentration is high in the first trial, and then it is followed by a decrease in second trial, in third and fourth trial it starts increasing and finally there is another decrease in fifth trial. It can be observed by looking at first and fifth trials that oxy-Hb in circular visuomotor rotation condition is always higher than linear visuomotor rotation condition at these two points. When investigated more closely, the difference in oxy-Hb during fifth trial is generally lower than first trial, and sometimes equal to first trial, but never higher. This can be interpreted as a function of adaptation to the task. Overall patterns in the figures suggest higher oxygenation for circular condition in at least three trials. However, in Channel 14, circular visuomotor rotation condition seems to have resulted in less oxy-Hb concentration than linear visuomotor rotation condition. This coincides with the results of Growth Curve Analysis reported above.

In most of the Channels with significant condition and consecutive trials interaction, oxy-Hb demonstrates same curvature in linear and circular conditions. However; in Channel 6, Channel 7, Channel 9 and Channel 15, while oxy-Hb follows a cubic pattern throughout trials in linear visuomotor rotation condition, this pattern can be seen as quadratic in circular visuomotor rotation condition (Figure 24-27). In all of these four Channels, oxy-Hb in circular condition is high in the first trial, it decreases throughout second, third and fourth trials and finally increases again at fifth trial. In linear condition, the change in oxy-Hb occurs in the same way described before in cubic patterns. In Channels 6, 7 and 9 it can be clearly observed that oxy-Hb in circular condition is higher than circular condition regardless of the shape of curvature. In only Channel 15 there is a decrease in circular condition during third and fourth trials, though higher oxygenation of circular condition is preserved for first, second and fifth trials.
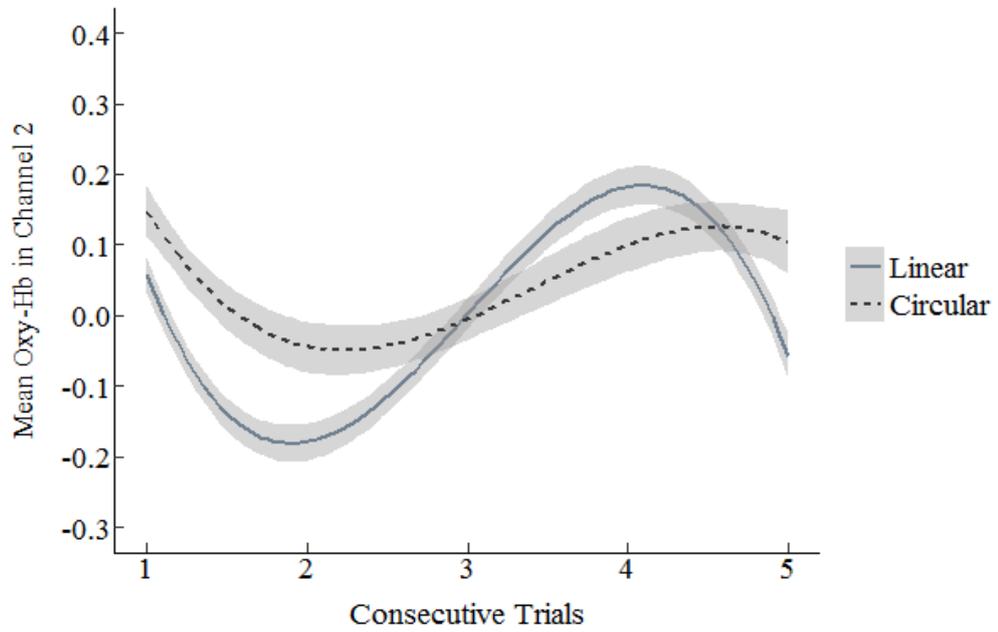
Figure 15. Mean (with 95% CI) oxygenated hemoglobin in Channel 2 throughout five consecutive visuomotor rotation trials in linear and circular conditions
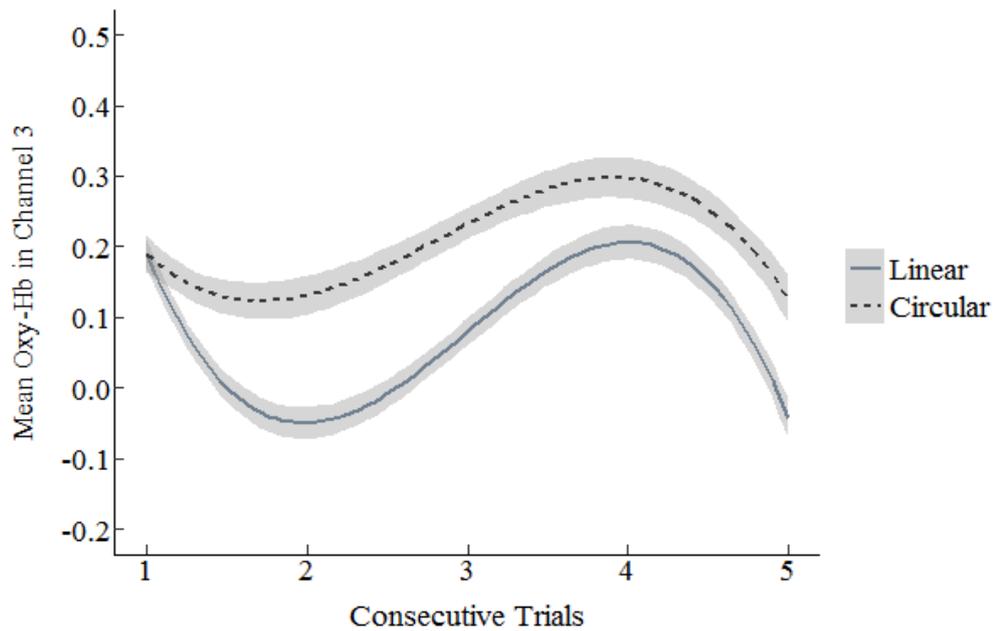
Figure 16. Mean (with 95% CI) oxygenated hemoglobin in Channel 3 throughout five consecutive visuomotor rotation trials in linear and circular conditions
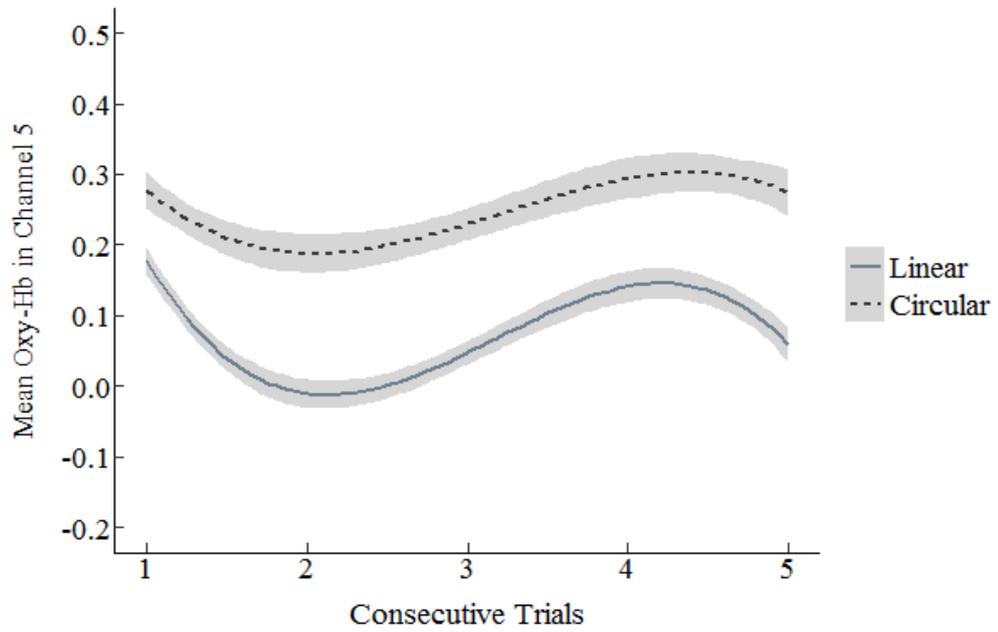
Figure 17. Mean (with 95% CI) oxygenated hemoglobin in Channel 5 throughout five consecutive visuomotor rotation trials in linear and circular conditions
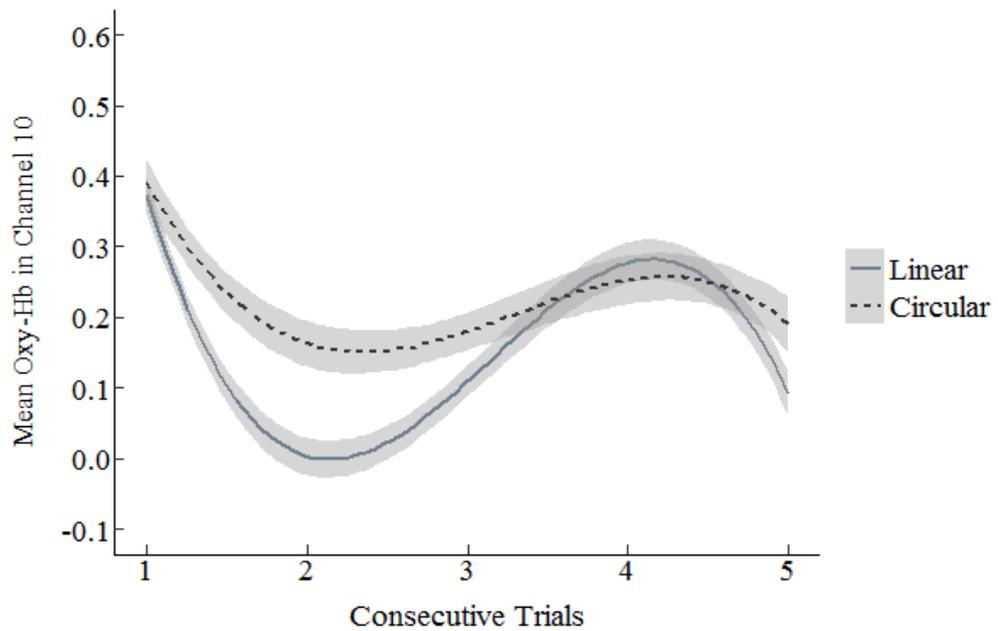
Figure 18. Mean (with 95% CI) oxygenated hemoglobin in Channel 10 throughout five consecutive visuomotor rotation trials in linear and circular conditions
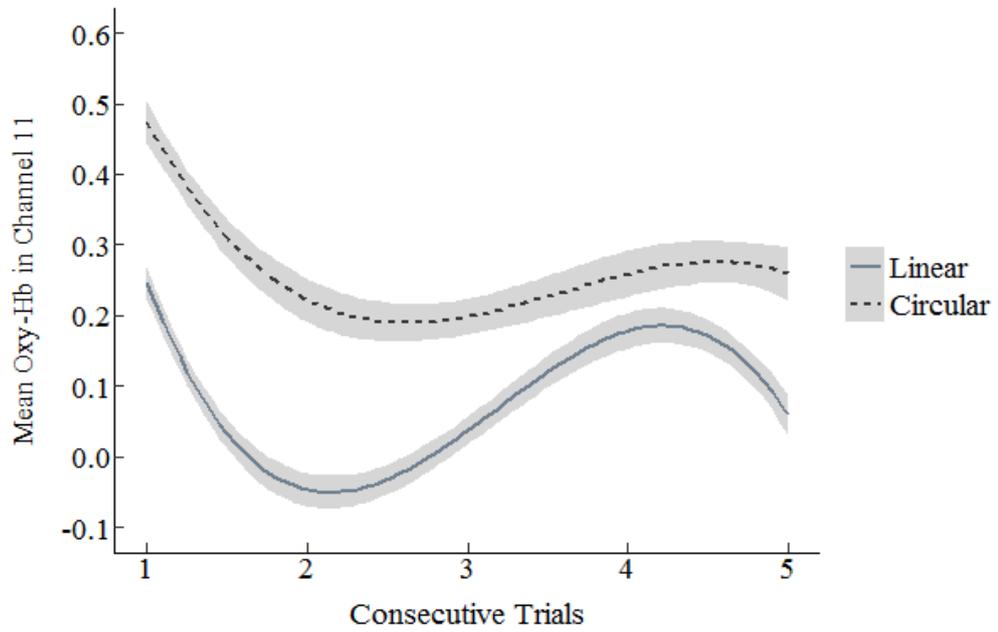
Figure 19. Mean (with 95% CI) oxygenated hemoglobin in Channel 11 throughout five consecutive visuomotor rotation trials in linear and circular conditions
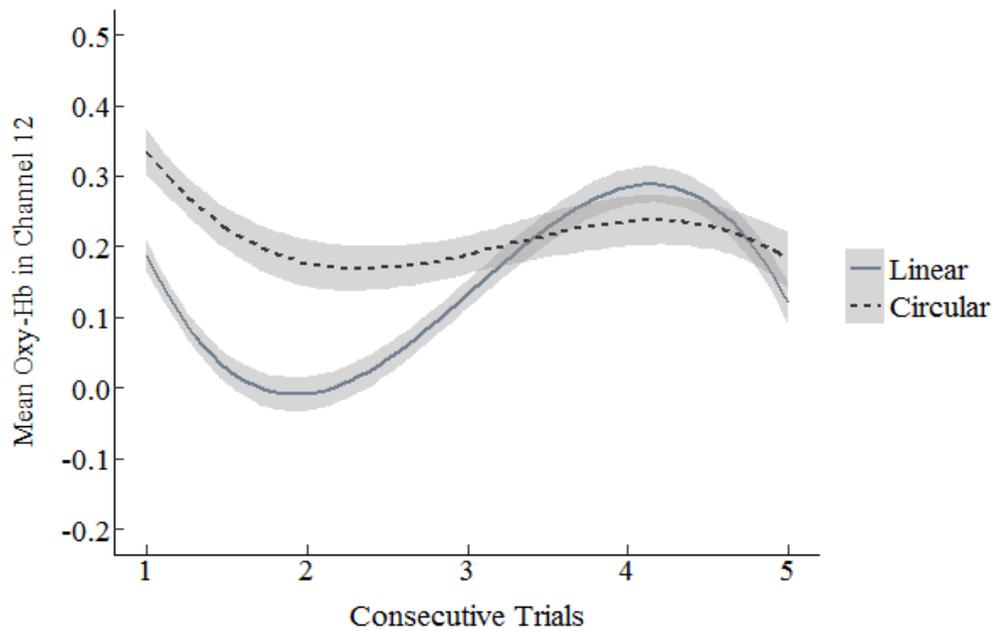
Figure 20. Mean (with 95% CI) oxygenated hemoglobin in Channel 12 throughout five consecutive visuomotor rotation trials in linear and circular conditions
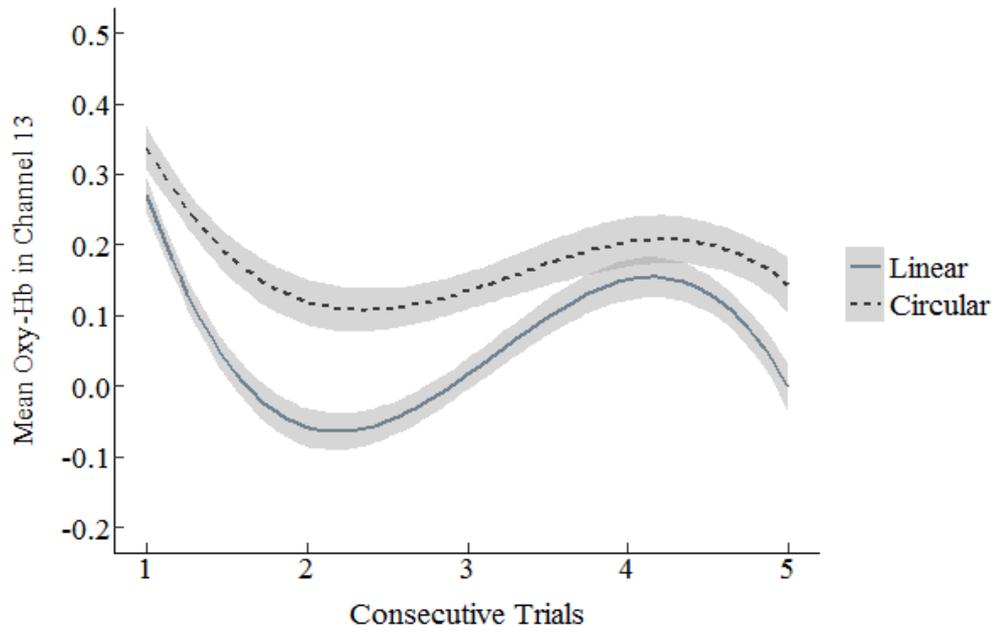
Figure 21. Mean (with 95% CI) oxygenated hemoglobin in Channel 13 throughout five consecutive visuomotor rotation trials in linear and circular conditions
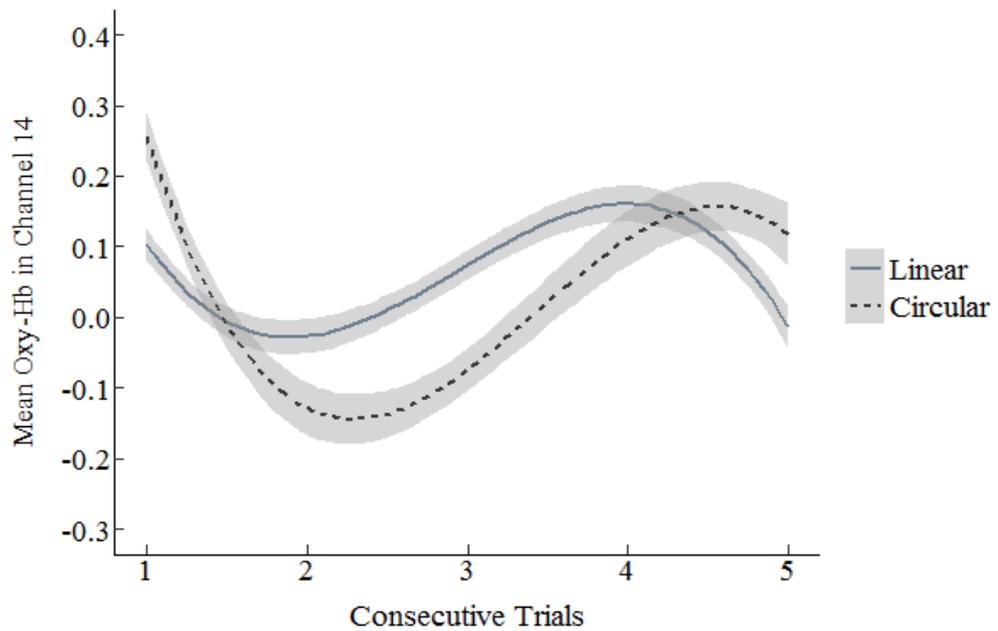
Figure 22. Mean (with 95% CI) oxygenated hemoglobin in Channel 14 throughout five consecutive visuomotor rotation trials in linear and circular conditions
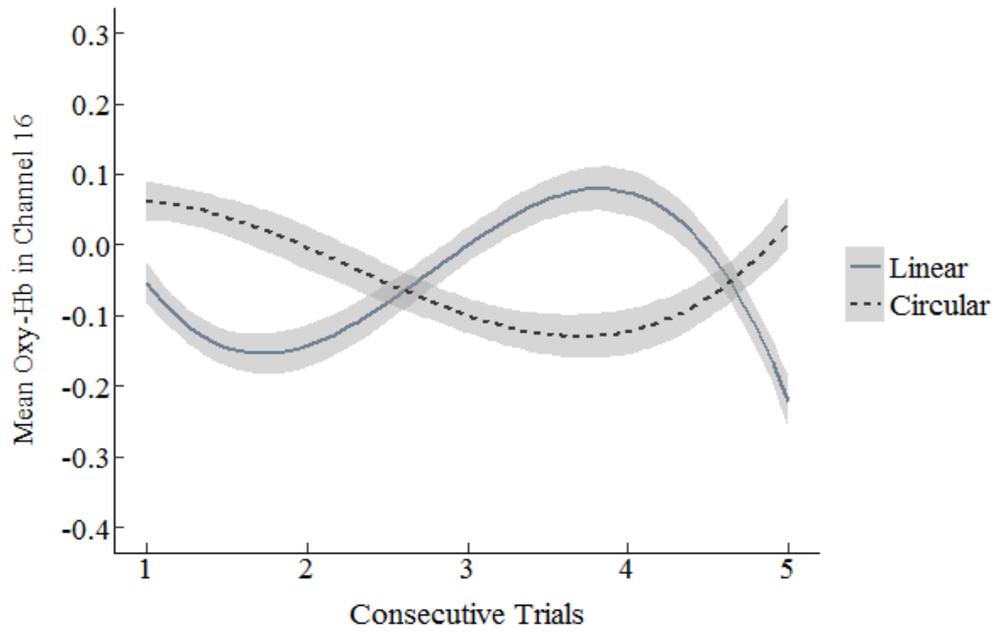
Figure 23. Mean (with 95% CI) oxygenated hemoglobin in Channel 16 throughout five consecutive visuomotor rotation trials in linear and circular condition
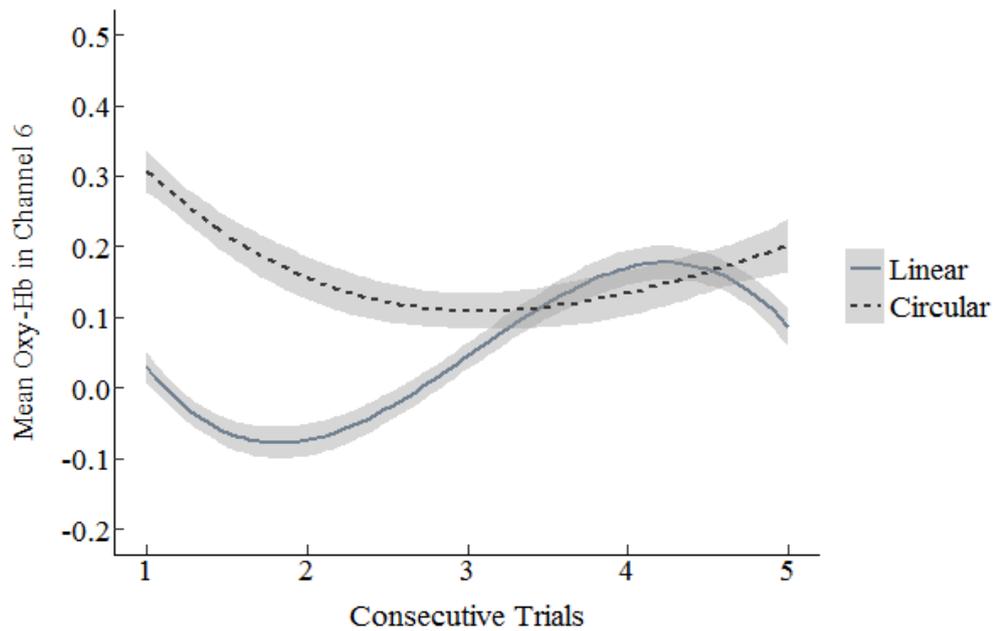
Figure 24. Mean (with 95% CI) oxygenated hemoglobin in Channel 6 throughout five consecutive visuomotor rotation trials in linear and circular conditions
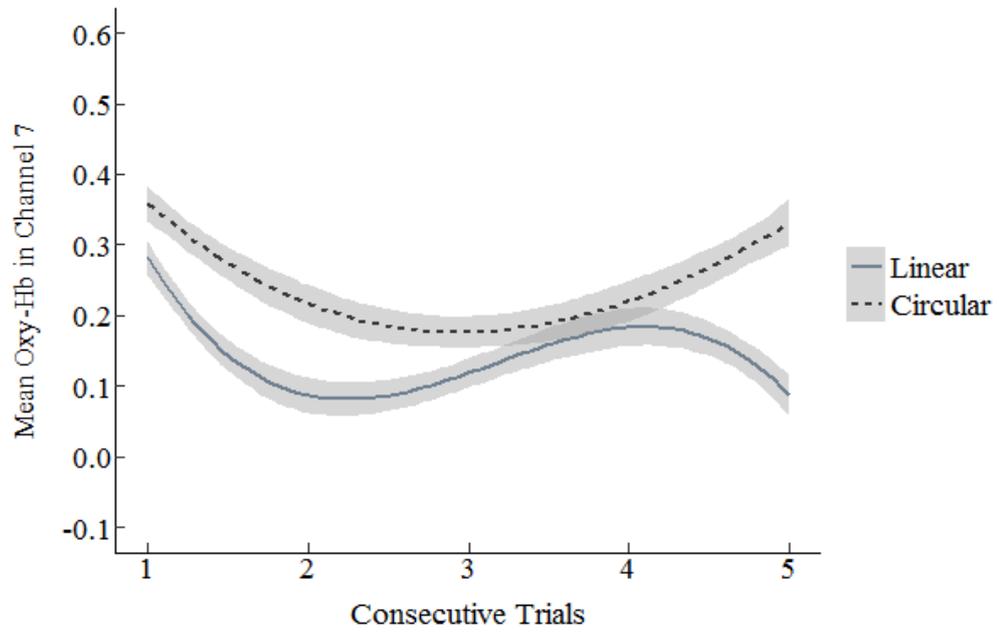
Figure 25. Mean (with 95% CI) oxygenated hemoglobin in Channel 7 throughout five consecutive visuomotor rotation trials in linear and circular conditions
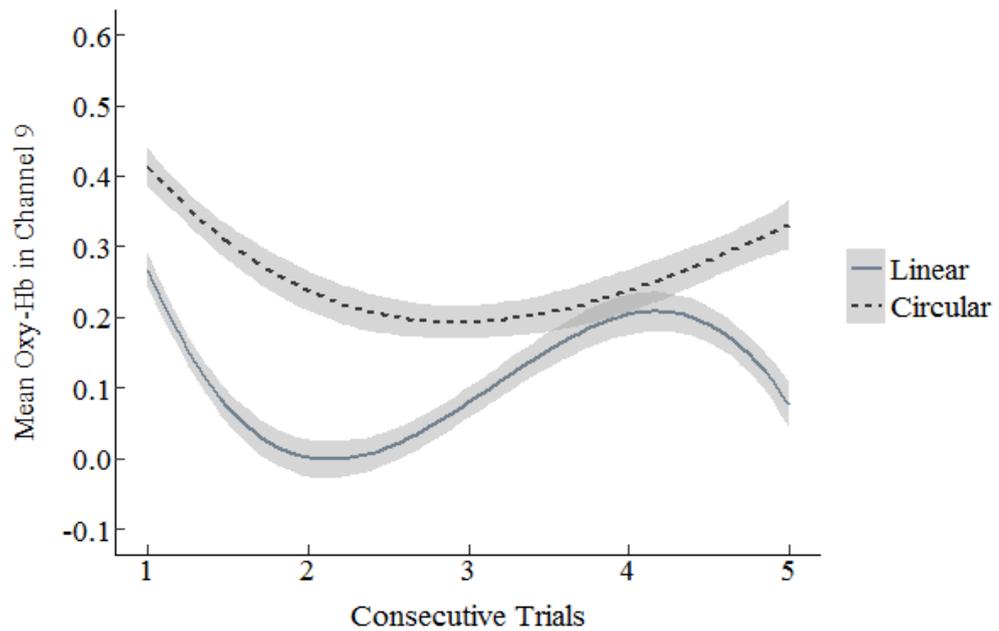
Figure 26. Mean (with 95% CI) oxygenated hemoglobin in Channel 9 throughout five consecutive visuomotor rotation trials in linear and circular conditions
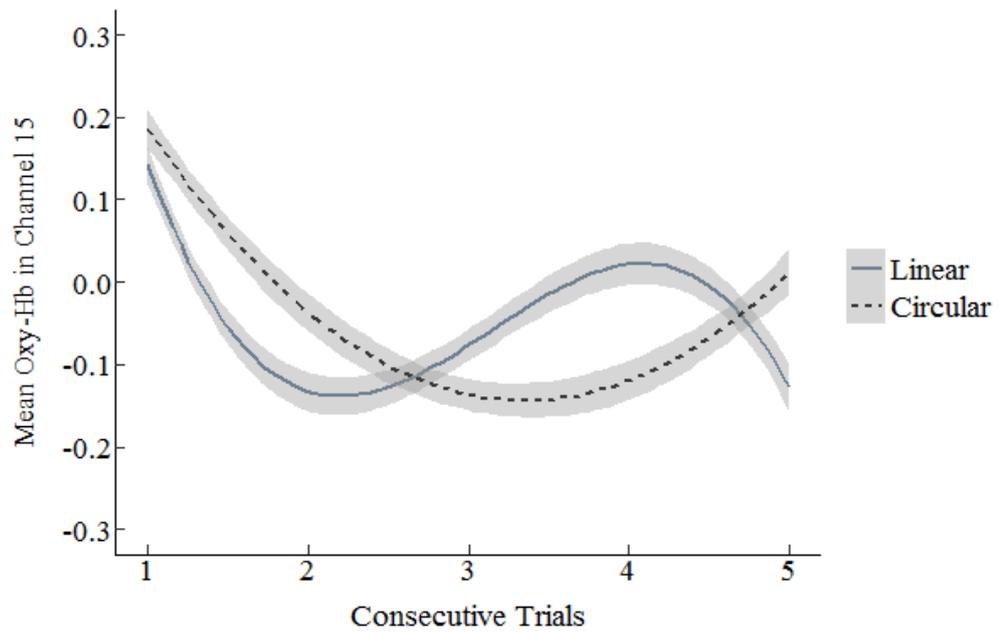
Figure 27. Mean (with 95% CI) oxygenated hemoglobin in Channel 15 throughout five consecutive visuomotor rotation trials in linear and circular conditions

Change in oxygenated hemoglobin in circular visuomotor rotation condition and linear visuomotor rotation condition throughout five consecutive trials was visualized using topography function in *f*NIR Soft Pro (Figure 28). The visualization method was chosen as interpolated-bordered B-spline. The lower and upper boundaries of for oxygenated hemoglobin were determined by calculating highest and lowest mean values and the criterion was specified as the overall mean. As it can be seen for circular condition; oxy-Hb concentration is high in first, third and fifth trials and low in second and fourth trials. In linear condition, oxy-Hb is high in first and fourth trials and almost the same in second, third and fifth trials with lower activity. Overall look at the figure suggests higher oxy-Hb in circular visuomotor rotation condition throughout trials, conceivably with the exception of fourth trial.

3.3.2.2. Deoxy-Hb

Growth Curve Analysis conducted for deoxy-Hb concentration suggested that the effect of condition on the intercept did not improve model fit for all of the 16-Channels: Channel 1, ($\chi^2_{(1)} = 0.33$, $p > .05$); Channel 2, ($\chi^2_{(1)} = 0.01$, $p > .05$); Channel 3, ($\chi^2_{(1)} = 0.02$, $p > .05$); Channel 4, ($\chi^2_{(1)} = 0.19$, $p > .05$); Channel 5, ($\chi^2_{(1)} = 2.18$, $p > .05$); Channel 6, ($\chi^2_{(1)} = 1.10$, $p > .05$); Channel 7, ($\chi^2_{(1)} = 0.00$, $p > .05$); Channel 8, ($\chi^2_{(1)} = 0.78$, $p > .05$); Channel 9, ($\chi^2_{(1)} = 0.10$, $p > .05$); Channel 10, ($\chi^2_{(1)} = 0.23$, $p > .05$); Channel 11, ($\chi^2_{(1)} = 0.49$, $p > .05$); Channel 12, ($\chi^2_{(1)} = 0.00$, $p > .05$); Channel 13, ($\chi^2_{(1)} = 0.01$, $p > .05$); Channel 14, ($\chi^2_{(1)} = 0.10$, $p > .05$); Channel 15, ($\chi^2_{(1)} = 0.06$, $p > .05$); and Channel 16, ($\chi^2_{(1)} = 2.28$, $p > .05$). However; the effect of condition on cubic term (slope) did improve the model fit in almost all of the Channels: Channel 1, ($\chi^2_{(3)} = 13.21$, $p < .05$); Channel 2, ($\chi^2_{(3)} = 129.39$, $p < .05$); Channel 3, ($\chi^2_{(3)} = 88.28$, $p < .05$); Channel 4, ($\chi^2_{(3)} = 83.10$, $p < .05$); Channel 5, ($\chi^2_{(3)} = 141.62$, $p < .05$); Channel 6, ($\chi^2_{(3)} = 39.15$, $p < .05$); Channel 7, ($\chi^2_{(3)} = 82.58$, $p < .05$); Channel 8, ($\chi^2_{(3)} = 188.58$, $p < .05$); Channel 9, ($\chi^2_{(3)} = 547.03$, $p < .05$); Channel 10, ($\chi^2_{(3)} = 233.42$, $p < .05$); Channel 11, ($\chi^2_{(3)} = 485.10$, $p < .05$); Channel 12, ($\chi^2_{(3)} = 228.99$, $p < .05$), Channel 13, ($\chi^2_{(3)} = 190.41$, $p < .05$), Channel 14, ($\chi^2_{(3)} = 109.38$, $p < .05$); Channel 16, ($\chi^2_{(3)} = 13.22$, $p > .05$), except Channel 15, ($\chi^2_{(3)} = 2.11$, $p > .05$) which indicated a non-significant interaction between experimental condition and cubic change in deoxy-Hb concentration throughout trials.
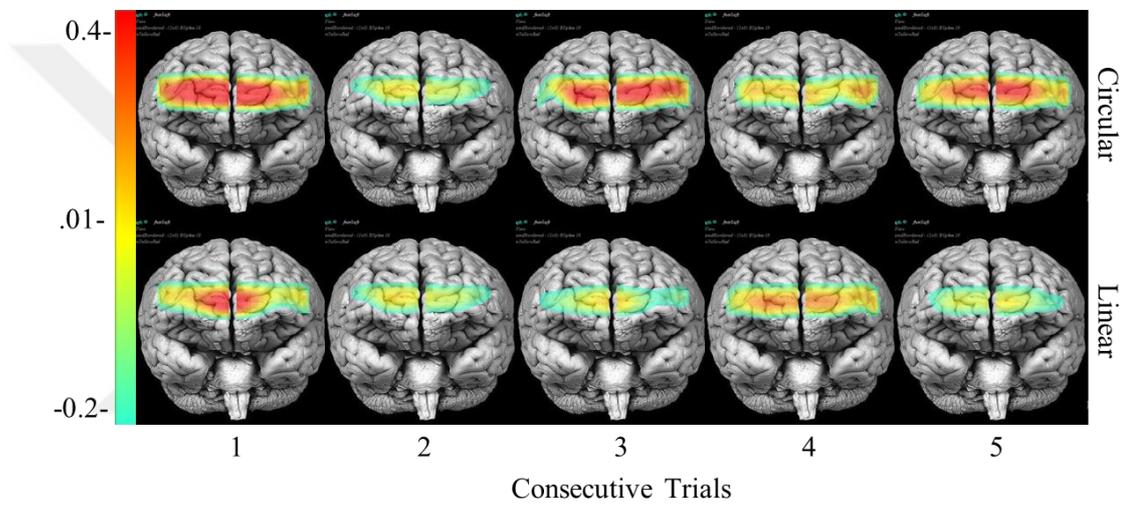
Figure 28. Mean oxygenated hemoglobin in linear and circular visuomotor conditions throughout consecutive trials

There was a significant random effect for the intercept in Channel 8, (*Estimate* = 0.11130, *SE* = 0.03880, *p* < .01); Channel 9, (*Estimate* = 0.10600, *SE* = 0.03981, *p* < .05); Channel 10, (*Estimate* = 0.12550, *SE* = 0.03517, *p* < .05); Channel 11, (*Estimate* = 0.08315, *SE* = 0.03644, *p* < .05); and Channel 12, (*Estimate* = 0.10200, *SE* = 0.03305, *p* < .05), indicating that initial deoxy-Hb during visuomotor rotation trials were highly diverse among the sample (Table 6).

There was also a significant effect of experimental condition on the cubic term in the following Channels: Channel 1, (*Estimate* = -0.03457, *SE* = 0.00993, *p* < .001); Channel 2, (*Estimate* = 0.11590, *SE* = 0.01036, *p* < .001); Channel 3, (*Estimate* = -0.09996, *SE* = 0.01106, *p* < .001); Channel 4, (*Estimate* = -0.12220, *SE* = 0.01348, *p* < .001); Channel 5, (*Estimate* = -0.13510, *SE* = 0.01154, *p* < .001); Channel 6, (*Estimate* = -0.06018, *SE* = 0.00968, *p* < .001); Channel 7, (*Estimate* = -0.10610, *SE* = 0.01197, *p* < .001); Channel 8, (*Estimate* = -0.16670, *SE* = 0.01213, *p* < .001); Channel 9, (*Estimate* = -0.29280, *SE* = 0.01239, *p* < .001); Channel 10, (*Estimate* = -0.20650, *SE* = 0.01355, *p* < .001); Channel 11, (*Estimate* = -0.26530, *SE* = 0.01191, *p* < .001); Channel 12, (*Estimate* = -0.13690, *SE* = 0.00901, *p* < .001); Channel 13, (*Estimate* = -0.15370, *SE* = 0.01113, *p* < .001); Channel 14, (*Estimate* = -0.13830, *SE* = 0.01324, *p* < .001); and Channel 16, (*Estimate* = 0.03025, *SE* = 0.01024, *p* < .01).

In almost all of the Channels given above, except Channel 2 and Channel 16, negative estimate value for the effect of experimental condition on the cubic term suggests a shallower curvature in circular visuomotor rotation condition than in linear visuomotor rotation condition. This means that; as trials progressed deoxy-Hb concentration throughout trials in circular condition was lower than linear condition. The exception of Channel 2 might be as a result of the effect of experimental condition is significant on linear term too. In Channel 16, main effect of experimental condition seems to have significant main effect on deoxy-Hb concentration with a negative estimate value, (*Estimate* = -0.19510, *SE* = 0.07905, *p* < .05). As linear visuomotor rotation condition is regarded as reference category in this analysis and it is extracted from circular visuomotor rotation condition, this result suggests that linear condition caused more deoxygenation concentration.

Table 6

Parameter Estimates for Analysis of Effect of Condition on Deoxygenated Hemoglobin

	Estimate	Std.Error	t	p
Channel 1				
Intercept	0.02022	0.02706	0.747	0.461
Linear	-0.02172	0.04691	-0.463	0.647
Quadratic	0.05406	0.06274	0.862	0.397
Cubic	-0.02695	0.00703	-3.836	0.000***
Circular: Intercept	0.01981	0.03898	0.508	0.615
Circular: Linear	0.05892	0.06758	0.872	0.390
Circular: Quadratic	-0.08508	0.09040	-0.941	0.355
Circular: Cubic	-0.03457	0.00993	-3.481	0.001***
Channel 2				
Intercept	0.06021	0.05295	1.137	0.266
Linear	-0.07429	0.05777	-1.286	0.210
Quadratic	-0.05810	0.05546	-1.048	0.304
Cubic	-0.01595	0.00749	-2.131	0.033*
Circular: Intercept	-0.08006	0.07487	-1.069	0.295
Circular: Linear	0.18300	0.08168	2.241	0.034*
Circular: Quadratic	0.03159	0.07840	0.403	0.690
Circular: Cubic	0.11590	0.01036	11.185	<2e-16***
Channel 3				
Intercept	0.05037	0.02742	1.837	0.077
Linear	-0.05971	0.04900	-1.219	0.234
Quadratic	0.04091	0.07779	0.526	0.603
Cubic	0.03846	0.00782	4.917	8.94e-07***
Circular: Intercept	-0.01598	0.03950	-0.405	0.689
Circular: Linear	0.19780	0.07059	2.802	0.093**
Circular: Quadratic	-0.07738	0.11210	-0.690	0.496
Circular: Cubic	-0.09996	0.01106	-9.039	<2e-16***

	Estimate	Std.Error	t	p
Channel 4				
Intercept	0.02446	0.04591	0.533	0.599
Linear	-0.04722	0.04935	-0.957	0.347
Quadratic	-0.00441	0.11880	-0.037	0.971
Cubic	0.08337	0.00973	8.569	<2e-16***
Circular: Intercept	-0.00900	0.06492	-0.139	0.891
Circular: Linear	0.10040	0.06975	1.440	0.162
Circular: Quadratic	-0.00203	0.16790	-0.012	0.990
Circular: Cubic	-0.12220	0.01348	-9.071	<2e-16***
Channel 5				
Intercept	0.01680	0.04237	0.397	0.695
Linear	-0.03315	0.04878	-0.679	0.503
Quadratic	-0.05073	0.05916	-0.858	0.399
Cubic	0.02622	0.00822	3.191	0.001**
Circular: Intercept	0.07984	0.06105	1.308	0.202
Circular: Linear	0.17350	0.07027	2.469	0.020*
Circular: Quadratic	-0.05735	0.08522	-0.673	0.508
Circular: Cubic	-0.13510	0.01154	-11.714	<2e-16***
Channel 6				
Intercept	0.03261	0.04282	0.762	0.453
Linear	0.22190	0.06696	0.331	0.743
Quadratic	-0.07743	0.08266	-0.937	0.357
Cubic	0.09080	0.00688	13.203	<2e-16***
Circular: Intercept	0.06583	0.06170	1.067	0.295
Circular: Linear	-0.06607	0.00649	-0.685	0.499
Circular: Quadratic	0.06168	0.11910	0.518	0.609
Circular: Cubic	-0.06018	0.00968	-0.219	5.21e-10***

	Estimate	Std.Error	t	p
Channel 7				
Intercept	0.04263	0.04690	0.909	0.371
Linear	-0.09661	0.06402	-1.509	0.142
Quadratic	-0.05830	0.04819	-1.210	0.237
Cubic	-0.01855	0.00850	-2.181	0.029*
Circular: Intercept	-0.03195	0.06758	-0.437	0.640
Circular: Linear	0.20210	0.09224	2.191	0.037*
Circular: Quadratic	0.00433	0.06942	0.062	0.951
Circular: Cubic	-0.10610	0.01197	-8.863	<2e-16***
Channel 8				
Intercept	0.11130	0.03886	2.865	0.008**
Linear	-0.07943	0.07243	-1.097	0.283
Quadratic	-0.05588	0.05537	-1.009	0.322
Cubic	0.02123	0.00845	2.514	0.012*
Circular: Intercept	0.03041	0.05718	0.532	0.599
Circular: Linear	0.10580	0.10660	0.933	0.330
Circular: Quadratic	-0.10730	0.08147	-0.317	0.199
Circular: Cubic	-0.16670	0.01213	-13.742	<2e-16***
Channel 9				
Intercept	0.10600	0.03981	2.664	0.013*
Linear	-0.02621	0.04681	-0.560	0.580
Quadratic	-0.04701	0.05775	-0.814	0.423
Cubic	0.02046	0.00879	-2.328	0.020*
Circular: Intercept	-0.05147	0.05736	-0.897	0.378
Circular: Linear	0.14510	0.06743	2.152	0.041*
Circular: Quadratic	-0.07318	0.08318	-0.880	0.387
Circular: Cubic	-0.29280	0.01239	-23.623	<2e-16***

	Estimate	Std.Error	t	p
Channel 10				
Intercept	0.12550	0.03517	3.568	0.001*
Linear	-0.05029	0.06935	-0.725	0.475
Quadratic	0.03392	0.06099	0.556	0.583
Cubic	-0.03821	0.00938	-4.072	4.71e-05***
Circular: Intercept	-0.04301	0.05176	-0.831	0.414
Circular: Linear	0.10160	0.10210	0.995	0.329
Circular: Quadratic	-0.20100	0.08974	-2.240	0.034*
Circular: Cubic	-0.20650	0.01355	-15.244	<2e-16***
Channel 11				
Intercept	0.08315	0.05712	2.282	0.031*
Linear	0.01348	0.11360	0.244	0.809
Quadratic	-0.05048	0.09326	-0.848	0.404
Cubic	0.05232	0.01486	6.314	2.83e-10***
Circular: Intercept	0.02687	0.08242	0.501	0.621
Circular: Linear	0.11460	0.18990	1.410	0.170
Circular: Quadratic	-0.09391	0.13450	-1.072	0.294
Circular: Cubic	-0.26530	0.02102	-22.271	<2e-16***
Channel 12				
Intercept	0.10200	0.03305	3.085	0.005*
Linear	0.04557	0.04997	0.912	0.370
Quadratic	-0.06190	0.04741	-1.306	0.203
Cubic	0.04992	0.00650	7.681	1.73e-14***
Circular: Intercept	-0.02357	0.04674	-0.504	0.618
Circular: Linear	0.05847	0.07065	0.828	0.417
Circular: Quadratic	-0.06918	0.06703	-1.032	0.312
Circular: Cubic	-0.13690	0.00901	-15.191	<2e-16***

	Estimate	Std.Error	t	p
Channel 13				
Intercept	0.04843	0.03157	1.525	0.140
Linear	0.02100	0.04915	0.427	0.673
Quadratic	-0.00262	0.04436	-0.059	0.953
Cubic	0.03509	0.00765	4.587	4.56e-06***
Circular: Intercept	-0.02096	0.04688	-0.447	0.659
Circular: Linear	0.09576	0.07258	1.319	0.199
Circular: Quadratic	-0.09563	0.06549	-1.460	0.157
Circular: Cubic	-0.15370	0.01113	-13.804	<2e-16***
Channel 14				
Intercept	0.03801	0.04493	0.846	0.406
Linear	0.10300	0.05518	1.866	0.074
Quadratic	-0.10240	0.11970	-0.856	0.400
Cubic	0.06791	0.00936	7.257	4.25e-13***
Circular: Intercept	-0.05666	0.06483	-0.874	0.390
Circular: Linear	0.04418	0.07961	0.555	0.584
Circular: Quadratic	0.10720	0.01727	0.621	0.540
Circular: Cubic	-0.13830	0.01324	-10.449	<2e-16***
Channel 16				
Intercept	0.04378	0.05590	0.783	0.441
Linear	-0.08650	0.06997	-1.236	0.228
Quadratic	0.01406	0.05706	0.247	0.807
Cubic	-0.03463	0.00738	-4.693	2.74e-06***
Circular: Intercept	-0.19510	0.07905	-2.468	0.021*
Circular: Linear	0.18820	0.09894	1.902	0.089
Circular: Quadratic	0.03601	0.08066	0.446	0.659
Circular: Cubic	0.03025	0.01024	2.953	0.003**

Signif. Codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "."

The significant interaction effect between experimental condition and cubic term (slope) was visualized for deoxy-Hb concentration throughout trials. It can be understood from the figures that in Channel 1, Channel 5, Channel 7, Channel 8, Channel 9, Channel 10, Channel 11, Channel 12 and Channel 13, deoxy-Hb in linear visuomotor rotation condition preserves a cubic pattern which has very small peaks in the curves (except for Channel 1); however, in circular visuomotor rotation condition the peaks in curves seem to be bigger and deoxy-Hb stays low through the first two trials, increasing in the third trial. (Figure 29-37). In Channel 5, Channel 7, Channel 8 and Channel 9, deoxy-Hb change in linear visuomotor rotation condition trials occurs in almost a quadratic pattern, with being high in first two trials and starting to decrease in third trial. In all of the Channels given above, deoxy-Hb in circular visuomotor rotation preserves a cubic pattern, showing higher deoxy-Hb in the third and fourth trials.

In Channel 2, Channel 3, Channel 4, Channel 6, Channel 14 and Channel 16, the pattern described above seems to be different (Figure 38-43). In Channel 2 deoxy-Hb in linear visuomotor rotation condition is higher than circular visuomotor rotation condition until the fifth trial. In linear visuomotor rotation condition it starts high in the first trial and decreases throughout trials in a quadratic pattern, while in circular visuomotor rotation condition the pattern remains cubic. However, the pattern is changed this time with an increase in second trial and a decrease in fourth trial, finalized with decrease in fifth trial. Deoxy-Hb in Channel 3 follows a quadratic pattern for linear visuomotor rotation condition with an increasing pattern until the fifth trial and remaining there. For circular condition it follows a cubic pattern with decrease in second trial and increase in fourth trial as described before for previous Channels. In Channel 4; deoxy-Hb changes throughout trials in a cubic pattern for both circular and linear visuomotor rotation conditions. Nevertheless, the curvatures have opposite natures. Meaning that for linear visuomotor condition deoxy-Hb is higher than circular condition in first two trials, same with it in third and fifth trials and lower than it in the fourth trial. For Channel 14, it can be seen that deoxy-Hb in both circular and linear conditions change in a cubic pattern, though it is different for linear condition as a dramatic increase can be observed following the first trial until
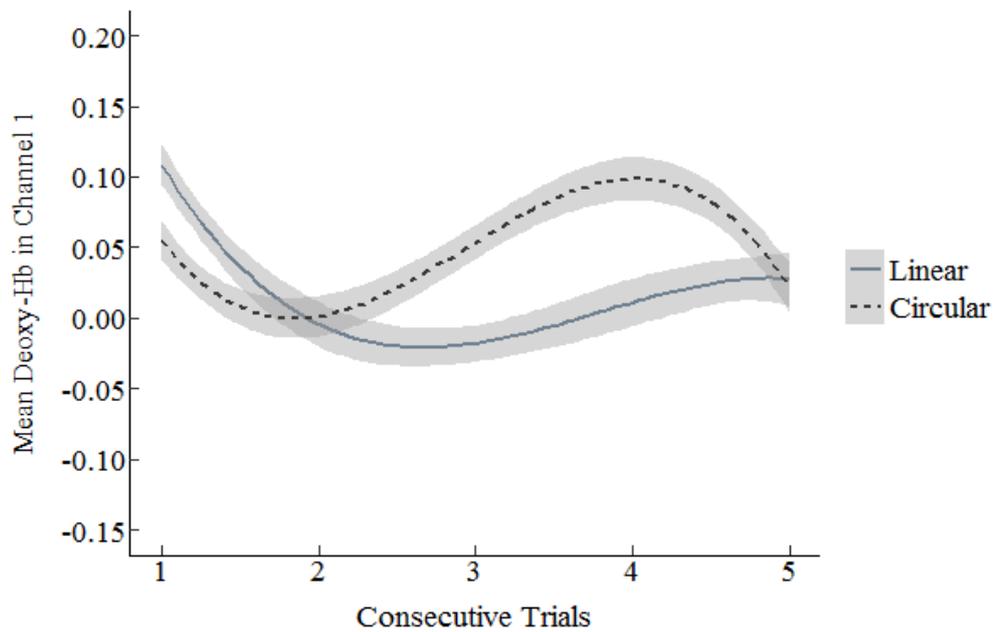
Figure 29. Mean (with 95% CI) deoxygenated hemoglobin in Channel 1 throughout five consecutive visuomotor rotation trials in linear and circular conditions
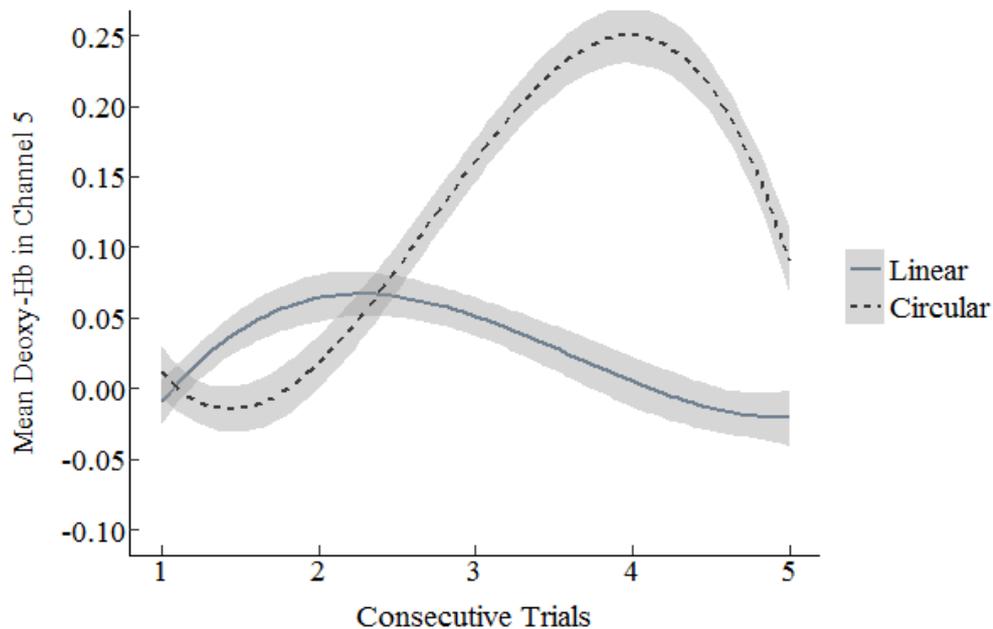
Figure 30. Mean (with 95% CI) deoxygenated hemoglobin in Channel 5 throughout five consecutive visuomotor rotation trials in linear and circular conditions
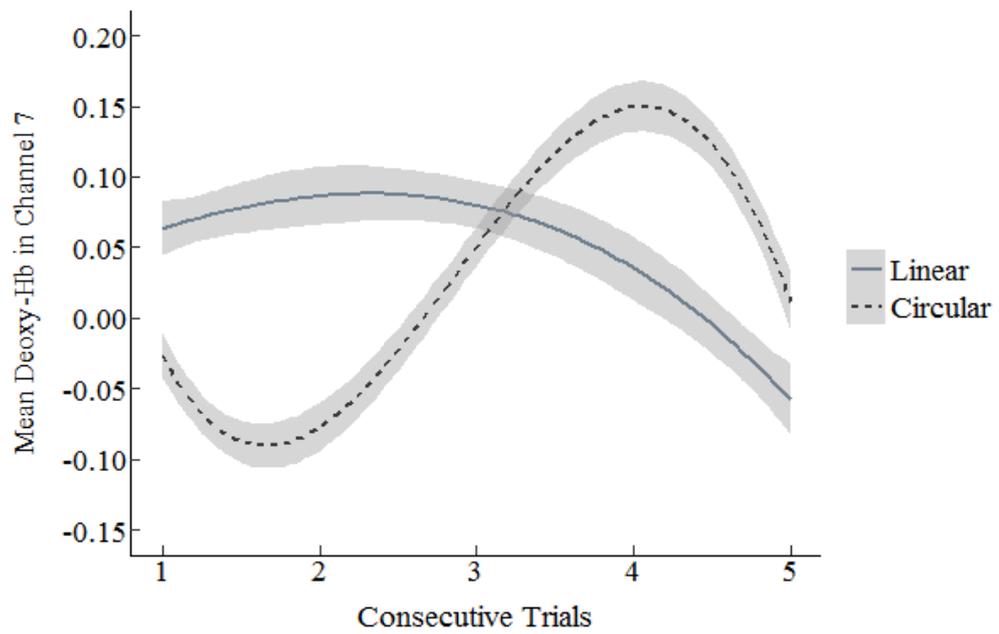
Figure 31. Mean (with 95% CI) deoxygenated hemoglobin in Channel 7 throughout five consecutive visuomotor rotation trials in linear and circular conditions
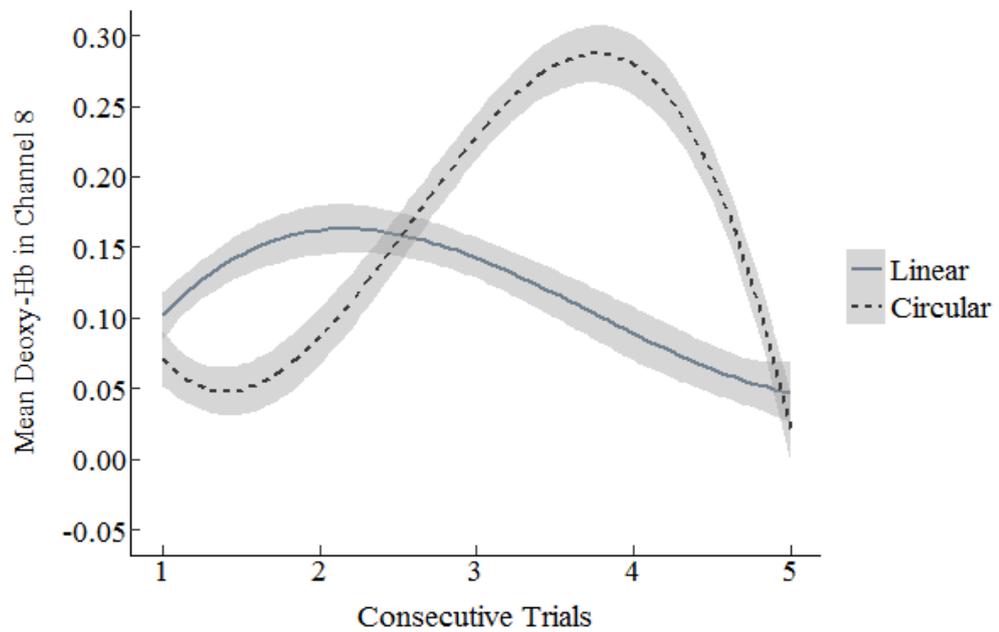
Figure 32. Mean (with 95% CI) deoxygenated hemoglobin in Channel 8 throughout five consecutive visuomotor rotation trials in linear and circular conditions
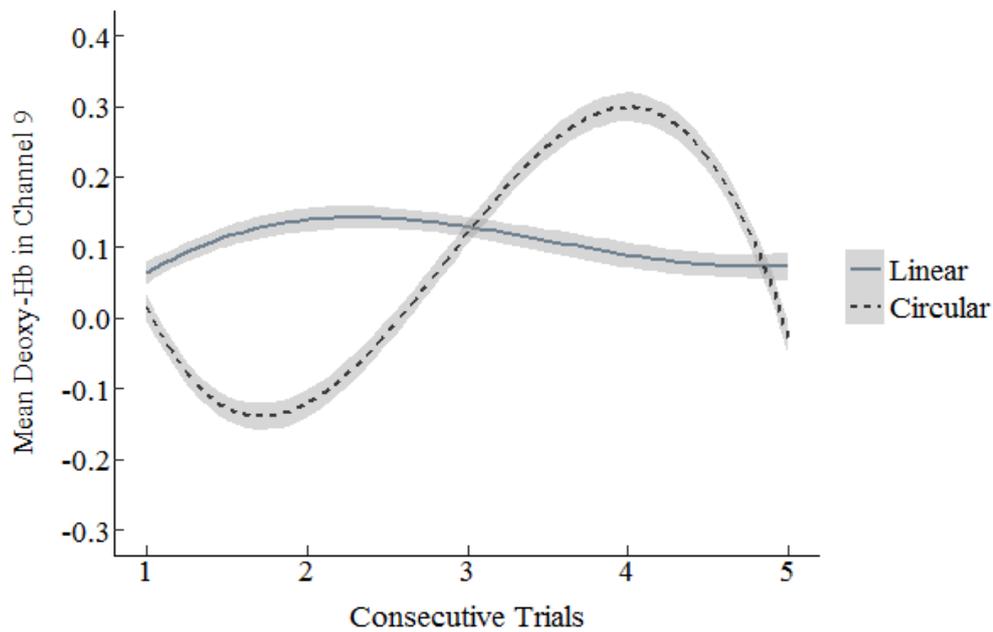
Figure 33. Mean (with 95% CI) deoxygenated hemoglobin in Channel 9 throughout five consecutive visuomotor rotation trials in linear and circular conditions
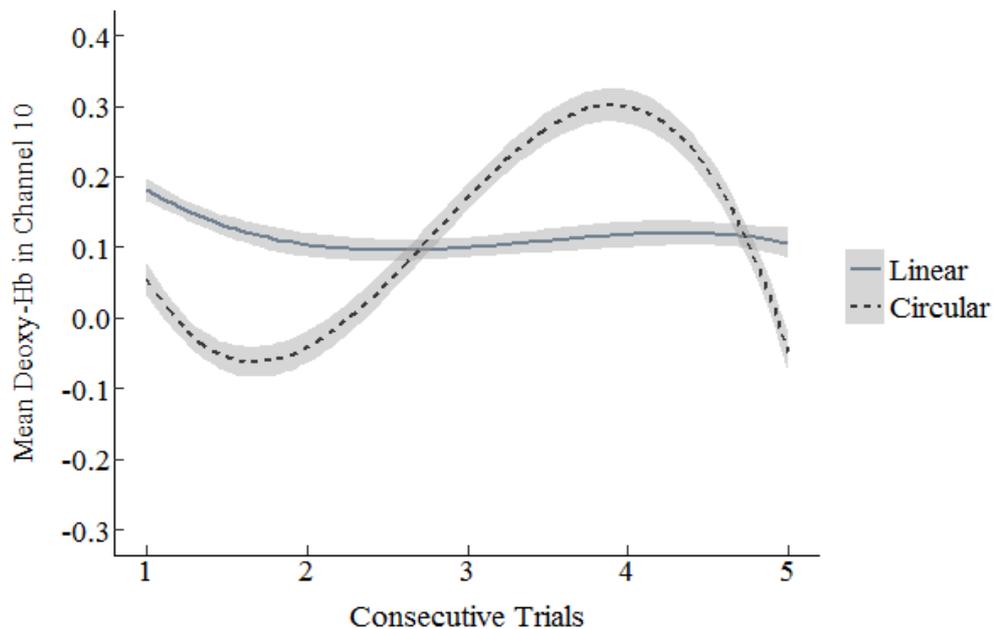
Figure 34. Mean (with 95% CI) deoxygenated hemoglobin in Channel 10 throughout five consecutive visuomotor rotation trials in linear and circular conditions
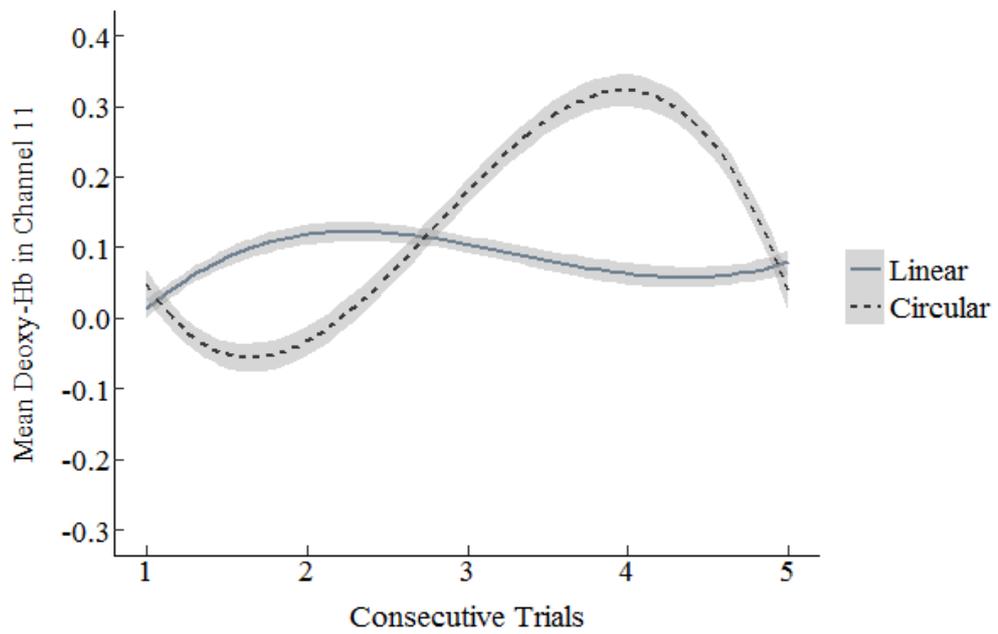
Figure 35. Mean (with 95% CI) deoxygenated hemoglobin in Channel 11 throughout five consecutive visuomotor rotation trials in linear and circular conditions
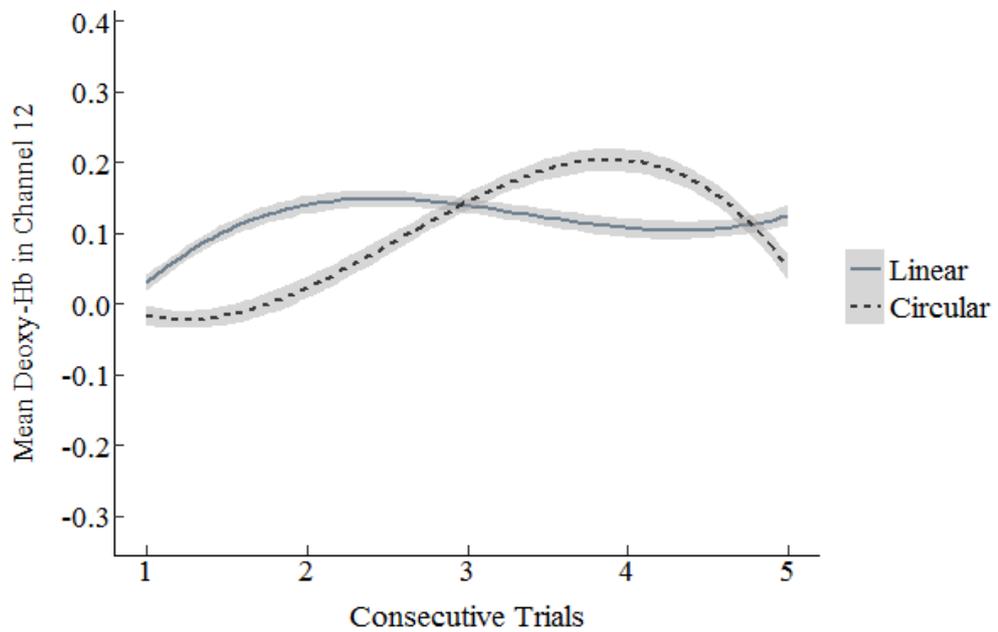
Figure 36. Mean (with 95% CI) deoxygenated hemoglobin in Channel 12 throughout five consecutive visuomotor rotation trials in linear and circular conditions
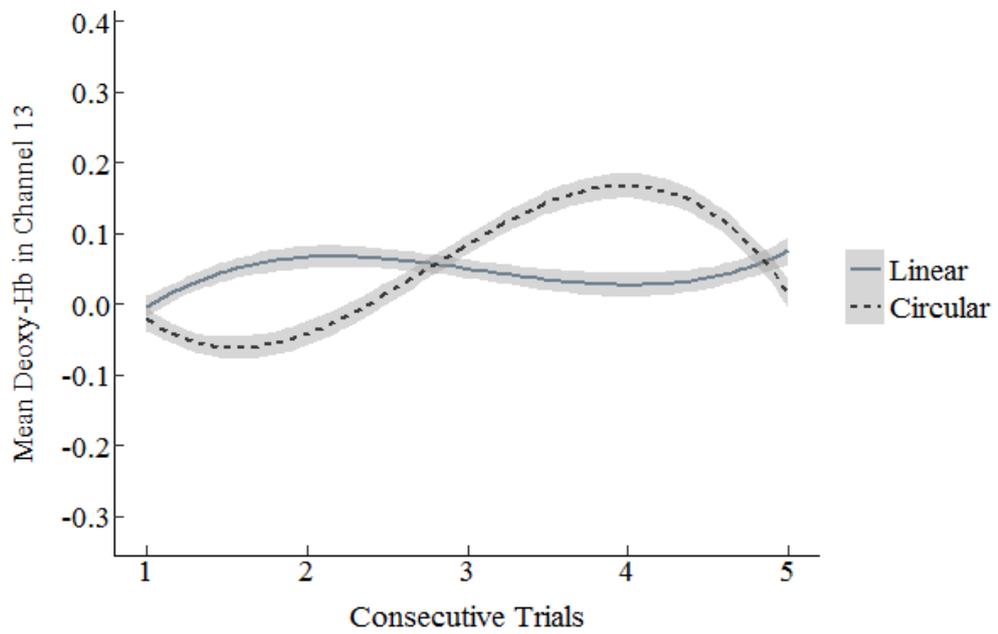
Figure 37. Mean (with 95% CI) deoxygenated hemoglobin in Channel 13 throughout five consecutive visuomotor rotation trials in linear and circular conditions
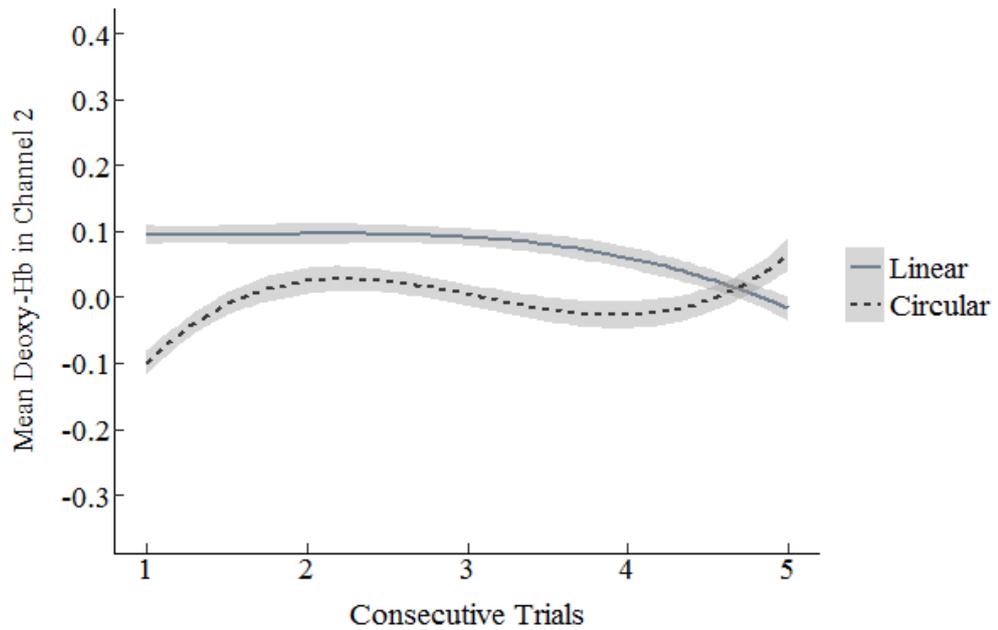
Figure 38. Mean (with 95% CI) deoxygenated hemoglobin in Channel 2 throughout five consecutive visuomotor rotation trials in linear and circular conditions
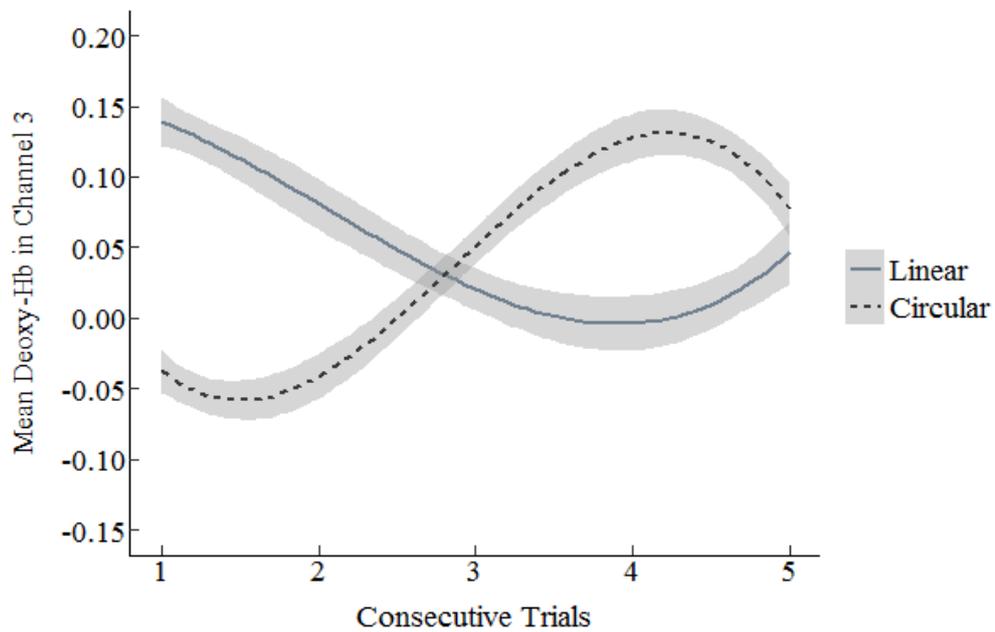
Figure 39. Mean (with 95% CI) deoxygenated hemoglobin in Channel 3 throughout five consecutive visuomotor rotation trials in linear and circular conditions
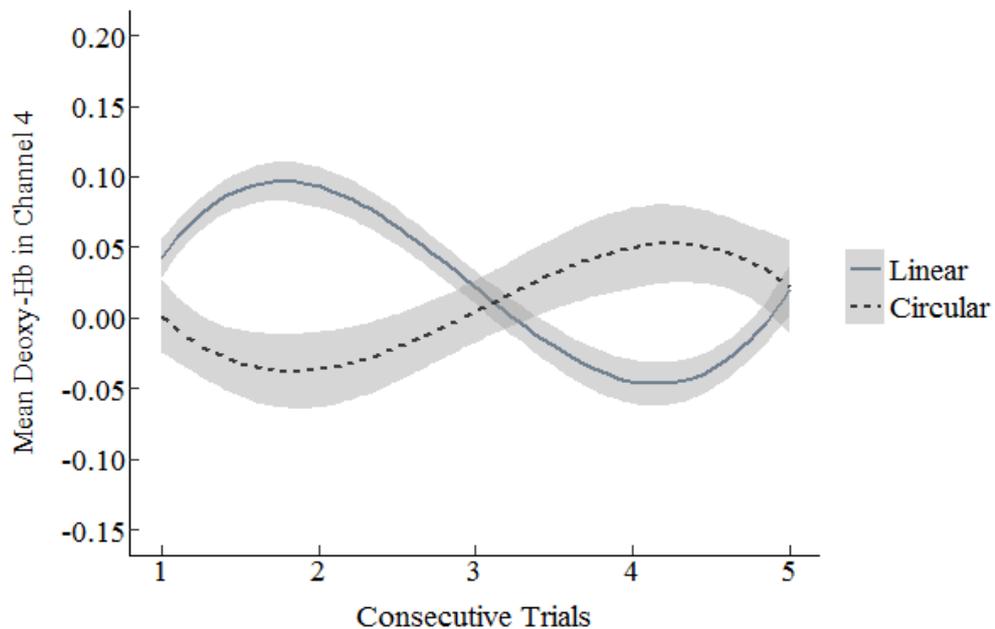
Figure 40. Mean (with 95% CI) deoxygenated hemoglobin in Channel 4 throughout five consecutive visuomotor rotation trials in linear and circular conditions
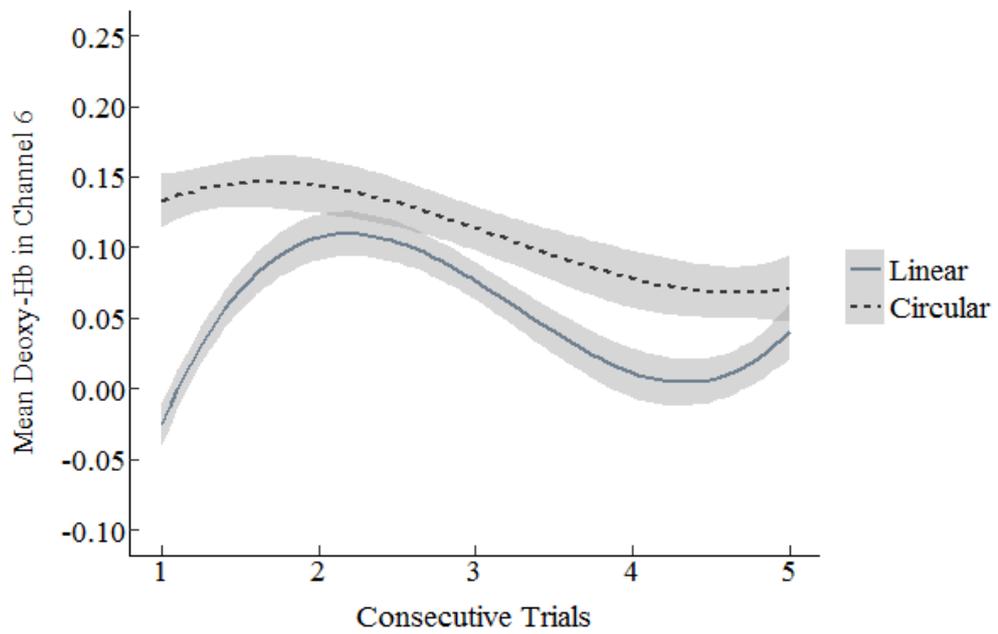
Figure 41. Mean (with 95% CI) deoxygenated hemoglobin in Channel 6 throughout five consecutive visuomotor rotation trials in linear and circular conditions
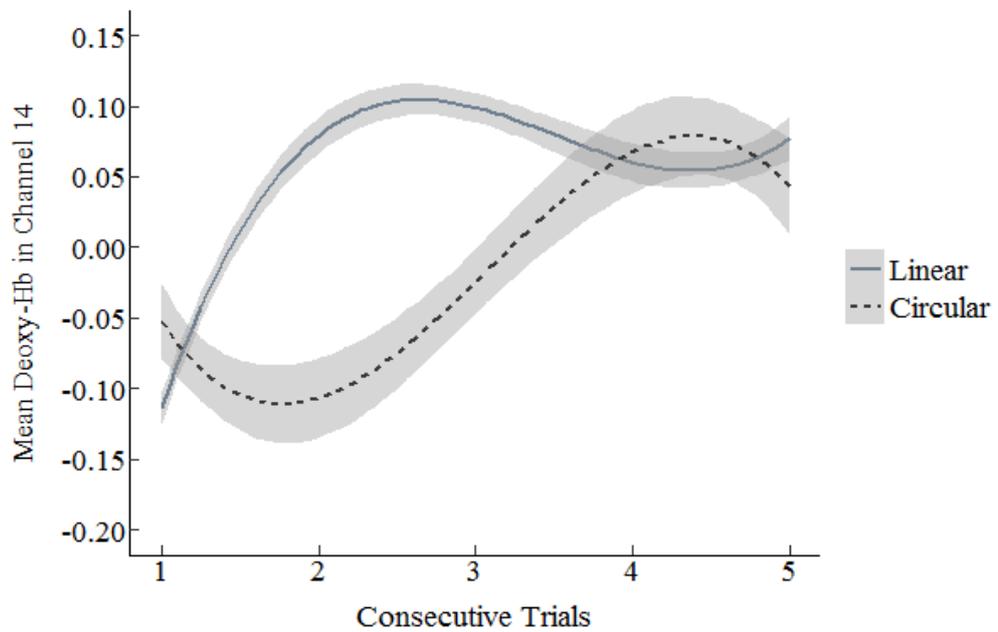
Figure 42. Mean (with 95% CI) deoxygenated hemoglobin in Channel 14 throughout five consecutive visuomotor rotation trials in linear and circular conditions
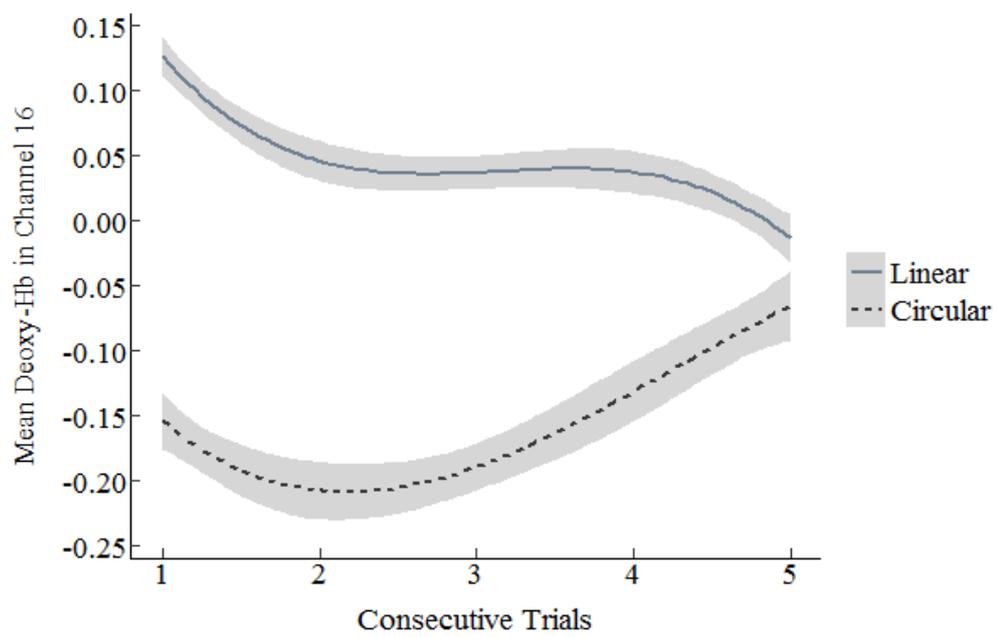
Figure 43. Mean (with 95% CI) deoxygenated hemoglobin in Channel 16 throughout five consecutive visuomotor rotation trials in linear and circular conditions

fourth trial. It decreases again for the fourth trial and finally increases again in the fifth trial. Probably the most peculiar pattern is observed in Channel 16, where deoxy-Hb shows an almost linear curve for both linear condition and circular conditions with linear condition remaining higher than circular condition throughout the trials. This coincides with the findings of Growth Curve Model fit on the data as results of Channel 16 indicated significant main effect of condition on deoxy-Hb levels and suggested that deoxy-Hb was higher in linear condition than circular condition and also a significant interaction effect between condition and linear curvature.

Aside from the interaction between experimental condition and cubic term, which is the main interest in this study, in some Channels there was also interaction between condition and linear or quadratic terms. In Channel 2, Channel 3, Channel 5, Channel 7, Channel 9 and Channel 16 there is significant effect of condition on linear term and in Channel 10, on the quadratic term. This might be a factor to keep in mind while investigating the figures in detail.

Deoxygenated hemoglobin changes in circular condition and linear condition throughout five consecutive trials was visualized using the identical method with oxy-Hb (Figure 44). Deoxy-Hb in circular visuomotor rotation condition seemed to be low in first, second and fifth trials and high in third and fourth trials. As for linear condition, deoxy-Hb seems to increase slightly in second, third and fourth trials and it is low in first and fifth trials. When examined as a whole it can be observed that during the first two and last visuomotor rotation trials deoxy-Hb is lower for the circular condition than linear condition and that the change in deoxy-Hb throughout trials seems to be stable for linear condition while there is a drastic peak for circular condition following the second trial.
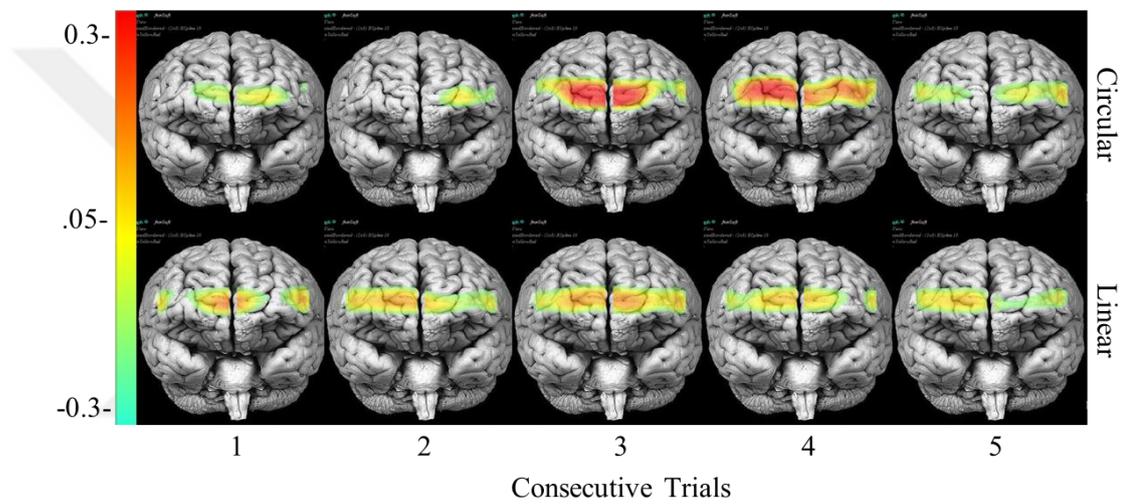
Figure 44. Mean deoxygenated hemoglobin in linear and circular visuomotor conditions throughout consecutive trials

CHAPTER IV

Discussion

The purpose of this study was to investigate the changes in eye-hand coordination and visual guidance provided by the eye to hands during adaptation to a novel visuomotor rotation task and the underlying neural correlates of this process. The novel visuomotor rotation task was distinct from traditional trajectory manipulation, known as CCW linear trajectory manipulation, in that it was not only a rotation manipulation but also a CCW nonlinear/circular trajectory manipulation which resulted in the cursor to perform rotated circular patterns after movement was initiated. In addition to applying circular trajectory manipulation, at every stage of the experiment; changes in eye-hand coordination and hemodynamic measurements throughout task performance were obtained for both linear trajectory manipulation and circular trajectory manipulation. This paved the way for a thorough analysis of each trajectory manipulation and also a comparative analysis related to these trajectories. Investigation of eye-hand coordination and hemodynamic response were carried out separately in two studies. Specific aim for Study 1 was to reveal the gradual changes that occur in eye-hand coordination during adaptation to linear and circular visuomotor rotation tasks and for Study 2, it was to observe and analyze the underlying neural mechanisms of visuomotor adaptation to linear and circular visuomotor rotation tasks.

The length of time participants spent to complete visuomotor rotation trials was included as the behavioral data for the analysis which, in other words, is the reaction time. Visual guidance was analyzed based on local components determined as time interval between first eye fixation on target and target hit (eye-to-shooting latency), time interval between first eye fixation on target and arrival of cursor on target (eye-to-hand latency), time interval between arrival of cursor in target area and target hit (hand-to-shooting latency), and time interval between first eye fixation on target and first eye fixation on the next target (eye-to-eye latency), all of which were obtained via an Eye Tracking Device. Underlying neural correlates of adaptation to circular

and traditional (linear) trajectory manipulation were obtained via *f*NIR Device as hemodynamic responses formed of local oxy-Hb concentration and deoxy-Hb concentration. For all of the measurements stated above, a comparison was provided between traditional trajectory manipulation (linear) and circular trajectory manipulation.

4.1. Changes in Reaction Time during Visuomotor Adaptation

The results of the Growth Curve Analysis conducted on behavioral data of Study 1 and Study 2, which was the length of time participants took to complete consecutive trials had some dissimilarities related to main effect of condition on trial completion length and interaction between condition and gradual change in trial completion length throughout trials. In Study 1, there was a main effect of condition on trial completion length which suggested participants in circular visuomotor rotation condition took longer time to complete trials than the participants in linear visuomotor rotation condition. Additionally, a significant main effect of trial was found indicating that as trials progressed, the amount of time participants took to complete trials decreased. However, the amount of time participants took to complete trials as trials progressed seemed to have remained uninfluenced by the experimental condition participants were assigned to. Based on the results of Study 1 hypothesis 1, which postulated that the change over time regarding the length of time participants spent to complete visuomotor rotation trials would occur in a decreasing pattern, was accepted. Similarly, as it was suggested in hypothesis 2, the overall length of time participants would spend to complete all trials differed between experimental conditions. Thus, hypothesis 2 was also accepted for Study 1. However, hypothesis 3, which assumed that the change over time regarding the length of time participants spent to complete trials would differ between experimental conditions, was rejected.

In Study 2, on the other hand, while the main effect of trial on trial completion time was preserved; the main effect of experimental condition on overall trial completion time was not observed. On the contrary, gradual change in the time participants took to complete trials throughout consecutive trials was influenced by the experimental condition participants were assigned to. The gradual decrease in trial completion time throughout trials was dissimilar for circular and linear visuomotor rotation conditions, with circular visuomotor rotation resulting in longer

trial completion time throughout trials. Considering the results of Study 2, while hypothesis 1 and hypothesis 3 were accepted, hypothesis 2 was rejected.

Though the applied tasks were the same and the analysis conducted on the baseline trial indicated no difference in linear visuomotor rotation and circular visuomotor rotation conditions, the observed difference regarding main effects and interaction effects might have resulted from a couple of reasons. First, the sample of Study 1 and Study 2 were not identical in number. While there were 32 participants in Study 1, there were 27 participants in Study 2 as some of them were excluded due to too much noise in hemodynamic measurements, meaning 5 participants less in Study 2. Second reason might be the differences in experiment chamber and device usage. While participants in Study 1 used the table to control the cursor and freely moved the mouse, in Study 2 it was a wooden prop which provided a more limited area for hand movements. Moreover, the utilized *f*NIR device constrained participants' movements as they were cautioned to keep their heads still throughout the experiment and its effects on hemodynamic measurements were emphasized. Therefore, participants first needed to adapt to the wooden prop and their position before adapting to trajectory manipulation itself. Third reason might be related to inter-trial interval. As Bock and colleagues (2005) also suggested, the length of inter-trial interval is an influential factor in visuomotor adaptation tasks. The inter-trial interval was 5 seconds in Study 1 while it was 15 seconds in Study 2 to obtain genuine resting period for baseline measurements. Therefore longer inter-trial interval might have minimized the effect of task difficulty aside when all trials were completed, while remaining effected by it during performing the tasks consecutively.

4.2. Eye-hand Coordination during Visuomotor Adaptation

The local components of eye-hand coordination, eye-to-shooting latency, eye-to-hand latency and hand-to-shooting latency, were also analyzed with Growth Curve Analysis regarding the gradual changes for each time interval throughout consecutive trials in linear and circular visuomotor rotation conditions. Findings of the analysis revealed a significant main effect of trial on eye-to-shooting latency and eye-to-eye latency as trials progressed and a significant main effect of experimental condition on eye-to-shooting latency and eye-to-eye latency which were both higher in circular visuomotor rotation condition trials than linear visuomotor rotation condition trials. There was a non-significant interaction effect between experimental condition and

progress of trials related to both measurements. None of the effects stated above were found to be significant for hand-to-shooting and eye-to-hand latencies. Based on this; hypothesis 4, which postulated that the change over time regarding the local components of eye-hand coordination stated as eye-to-shooting latency, eye-to-hand latency and hand-to-shooting latency would occur in a decreasing pattern, was accepted for eye-to-shooting latency and eye-to-eye latency. And hypothesis 5, which held the expectation of a significant effect of condition on overall changes in eye-to-shooting latency, eye-to-hand latency, hand-to-shooting latency and eye-to-eye latency, was also accepted for eye-to-shooting latency and eye-to-shooting latency with the time interval being higher for circular visuomotor rotation condition than linear visuomotor rotation condition. On the other hand, hypothesis 6 suggesting that the change over time regarding the local components of eye-hand coordination stated as eye-to-shooting latency, eye-to-hand latency, hand-to-shooting latency, and eye-to-eye latency would differ between experimental conditions, was rejected for all of the parameters.

Eye-to-shooting latency was included as a significant predictor of visuomotor adaptation as the reliance of hands on the visual guidance was demonstrated to have decreased throughout trials. Regarding non-significant results of hand-to-shooting latency and eye-to-hand latency; the only reasonable explanation, because the initial time intervals were found to be similar for both experimental groups in baseline trial, would be that they are actually divided portions of eye-to-shooting latency. More clearly, eye fixation is the first point of interest and target hit is the last point of interest and manual response is between these two points, segregating them. Therefore, the time window between eye fixation and target hit is divided into two by eye-to-hand and hand-to-shooting latencies. Division of time window apparently limited the content and power of eye-to-hand and hand-to-shooting latencies and thus, might have led to non-significant results.

Nonetheless; eye-to-shooting latency provided sufficient proof for the changes in eye-hand coordination and adaptation to the novel visuomotor mapping rule, since decrease in the time interval between first eye fixation and target hit indicates increase in speed, decrease in error and improvement in movement precision. Eye is the first organ to visit the target and the closer it is followed by the target hit, the less is the trouble experienced by the hand owing to rotation manipulation. Since eye-to-

shooting latency consists of both eye-to-hand latency and hand-to-shooting latency, it is capable of supplying information covering for both parameters in a united perspective. Since there is a linear decrease in the gradual change of eye-to-shooting latency supported by a significant effect of trial on this change, it is apparent that during the first trial time interval between first eye fixation and target hit is at its highest level. This means that when participants first came across with a rotation manipulation in the cursor's trajectory, they experienced some trouble in hitting the target in close time after the eye located the target and fixated on it. During the following trials this time interval decreased gradually and at each trial, it was lower than the previous. Moreover, when all trials were considered as whole and the gradual change was put aside, eye-to-shooting latency turned out to be longer for circular visuomotor rotation than linear visuomotor rotation, which suggested that the changes in eye-hand coordination were also influenced by the kind of trajectory manipulation applied on the cursor.

Eye-to-eye latency was included to examine the shift of eyes from exploratory point of view to predictive point of view. The time interval between first eye fixation to a target and first eye fixation on the next target is an indicator of how well participants adapted to the presented environment and decrease in this time interval suggests that participants learned the sequence of imminent targets and gained more control over the sensorimotor map. Furthermore; it signals that the eyes are no longer on the exploratory stage, where main focus is to understand the rule change and the outcomes of this change, but rather on the predictive stage in which the eye is able to detect next target in shorter time than previous trials.

4.3. Hemodynamic Response during Visuomotor Adaptation

Hemodynamic responses in participants' prefrontal cortex was obtained as local oxy-Hb and deoxy-Hb concentrations and were analyzed separately based on changes in concentration in linear visuomotor rotation and circular visuomotor rotation conditions throughout trials using Growth Curve Analysis. Since the gradual change throughout trials had a cubic pattern, cubic time term was fit to data to capture these changes. There was a significant main effect of cubic term (slope) on oxy-Hb concentration and deoxy-Hb concentration in all significant optodes, indicating that local oxy-Hb concentration and deoxy-Hb concentration changed throughout trials. This supported hypothesis 7: oxy-Hb and deoxy-Hb concentrations

would demonstrate changes throughout five consecutive trials. Therefore hypothesis 7 was accepted for both oxy-Hb concentration and deoxy-Hb concentration. The main effect of experimental condition on oxy-Hb and deoxy-Hb concentration, however, failed to improve model fit in all optodes for both hemodynamic measurements, which resulted in the rejection of hypothesis 8: The overall change in oxy-Hb and deoxy-Hb in all trials will differ between experimental conditions (linear visuomotor rotation and circular visuomotor rotation). To the contrary, the gradual change in local oxy-Hb concentration and deoxy-Hb concentration throughout trials changed depending on which experimental condition participants were assigned to, and as hypothesis 9 suggested that the changes over time regarding oxy-Hb concentration and deoxy-Hb concentration would differ between experimental conditions, it was accepted. And the effect of experimental condition on this gradual change revealed that oxy-Hb concentration was higher in circular visuomotor rotation than linear visuomotor rotation throughout trials, and that deoxy-Hb concentration was lower for circular visuomotor rotation than linear visuomotor rotation throughout trials.

The results that were mentioned in the previous paragraph were further supported by both figures generated based on the influence of condition on gradual change and topographies generated based on mean oxy-Hb concentration and deoxy-Hb concentration in linear visuomotor rotation and circular visuomotor rotation conditions throughout trials. In majority of the figures demonstrating the effect of experimental condition on the gradual change throughout trials related to oxy-Hb concentration, it was observed that this gradual change occurred in a cubic pattern and in minority of the figures it occurred in a quadratic pattern. The pattern was observed to be quadratic for optodes in which the effect of experimental condition on quadratic time term (slope) was also found to be significant. Other than that, most of the figures suggested a cubic change pattern with higher oxy-Hb concentration in circular visuomotor adaptation condition than linear visuomotor adaptation condition.

As for the figures generated for deoxy-Hb concentration, the gradual change also seemed to occur in a cubic pattern in some of the optodes and quadratic in some others. There was no majority related to gradual change pattern. In addition to cubic and quadratic patterns, linear pattern was also observed in a few optodes for both

conditions. This observation was seen in optodes which had significant interaction between experimental condition and linear time term (slope). Overall look at figures related to deoxy-Hb indicated higher deoxy-Hb concentration for linear visuomotor rotation condition than circular visuomotor rotation condition. This difference was also demonstrated by the estimate values obtained from Growth Curve Analysis.

The visualization of changes in oxy-Hb concentration in linear visuomotor rotation and circular visuomotor rotation condition throughout trials produced as topography supported the cubic pattern in circular visuomotor rotation condition and suggested a relatively quadratic pattern in linear visuomotor rotation condition. When observed regardless of the pattern, circular visuomotor rotation condition resulted in higher oxy-Hb concentration in almost all the trials than linear visuomotor rotation condition. Therefore, it is not farfetched to suggest that while participants performed circular visuomotor rotation task, hemoglobin located in prefrontal cortex required more oxygen. This provided additional proof to the fact that circular visuomotor rotation task was more difficult to perform than linear visuomotor rotation task.

The topographies created regarding the changes in local deoxy-Hb concentration for linear visuomotor rotation and circular visuomotor rotation conditions throughout trials suggested an almost quadratic pattern for circular visuomotor rotation condition and a linear pattern in linear visuomotor rotation condition. Laying aside the change pattern it can be seen that in three out of five trials, deoxy-Hb concentration is higher for linear visuomotor rotation condition than circular visuomotor rotation condition. Only in third and fourth trials deoxy-Hb concentration is higher in circular visuomotor rotation condition. This suggests that local deoxy-Hb concentration was observed to be higher during participants completed a relatively easier task. Moreover, as during the first two trials of circular visuomotor rotation deoxy-Hb concentration was low and it increased in third trial, it can be suggested that first two trials were more struggling than the following trials.

Since any brain activity occurring in the brain requires cerebral blood flow and during this process, which is referred to as neurovascular coupling, hemodynamic response is produced. Production of hemodynamic response is achieved by a change in the oxygenation state of local hemoglobin (Liao et al., 2013; Rahman and Ahmad, 2016). This change in cerebral blood, therefore, indicates neural activity in that

region. According to Strangman and colleagues (2002), a prototypical hemodynamic response results in an increase in cerebral blood flow in the active region and also increase in blood volume starting within 1-3 seconds of the activity. The changes observed in hemodynamic response are related to oxygenated state of hemoglobin, when oxyhemoglobin absorbs oxygen, and deoxygenated state of hemoglobin, when oxyhemoglobin gives up its oxygen (Disbrow et al., 2000). During neural activity, local oxy-Hb concentration and local deoxy-Hb concentration are negatively correlated and as a matter of fact, when they are not negatively correlated it is suggested that the obtained signals contain large amount of noise (Cui et al., 2010). Thus, when local oxy-Hb concentration increases, local deoxy-Hb concentration should decrease, or vice versa. When activity in a region is tried to be assessed; since oxyhemoglobin absorbs oxygen during this process, an increase in local oxy-Hb concentration serves as an efficient predictor. Indeed, some studies which investigated the changes in hemodynamic response after presenting tasks that would trigger activity in a region, interpreted increase in local oxy-Hb concentration as indicator of regional activity (Ayaz et al., 2011; Rahman and Ahmad, 2016). Moreover; in these studies if local oxy-Hb concentration was higher in either one of experimental conditions, than this condition was suggested to have resulted in more necessity of oxygen consumption by local oxyhemoglobin.

Therefore, based on the fact activity in brain is interpreted as an increase in oxy-Hb concentration and decrease in deoxy-Hb concentration owing to the negative relationship between local oxy-Hb and deoxy-Hb concentrations; it is clear that circular visuomotor rotation condition caused more necessity for oxygen consumption in participants' prefrontal cortex compared to linear visuomotor rotation condition since it caused oxy-Hb concentration to be higher and deoxy-Hb concentration to be lower in the local region. This provided additional support to the difference between the two trajectory manipulations in terms of task difficulty.

The information related to the specific locations in these activities can be obtained from the regions that coincide with the channels in a 16-channel ƒNIR device. Channels 1, 2, 3 and 4 correspond to left dorsolateral prefrontal cortex (LDLPFC); channels 5, 6, 7 and 8 correspond to left medial prefrontal cortex (LMPFC); channels 9, 10, 11, and 12 correspond to right medial prefrontal cortex (RMPFC); channels 13, 14, 15 and 16 correspond to right dorsolateral prefrontal

cortex (RDLPFC) (Liang et al., 2016). In a more specified point of view; channel 2 and 4 coincides with left ventrolateral prefrontal cortex (LVLPFC) and channel 14 and 16 coincide with right ventrolateral cortex (RVLPFC), located near dorsolateral prefrontal cortex (DLPFC) (Ayaz et al., 2010; McKendrick et al., 2014). Based on these statements; both by regarding the results of Growth Curve Analysis and generated topographies, there were significant changes in majority of these channels related to oxy-Hb concentration and deoxy-Hb concentration in both dorsolateral prefrontal cortex (DLPFC) and ventrolateral prefrontal cortex (VLPFC).

4.4. General Summary and Conclusions

The significant changes in oxy-Hb and deoxy-Hb concentrations which occurred in dorsolateral prefrontal cortex corresponded with the findings in aforementioned studies; (Floyer-Lea and Matthews, 2004; Halsband and Lange, 2006; Gentili et al., 2010; Seidler and Noll, 2008), suggesting the involvement of DLPFC during early stages of sensorimotor adaptation. As for the involvement of ventrolateral prefrontal cortex; it was postulated that, since VLPFC is stated to be active during motor activity control and inhibition of motor behavior (Levy et al., 2011), it would be possible to observe activity based changes in this region related to hemodynamic response. Indeed, this approximation was supported by the results of this study since both oxy-Hb concentration and deoxy-Hb concentration demonstrated changes in channels that coincide with VLPFC. Additionally; an overall activity was observed in prefrontal cortex inferred from the numerous activated channels and this supported the involvement of prefrontal cortex especially in early phases of motor learning (Goldman-Rakic, 1987), owing to the association of visuomotor adaptation with working memory and visuospatial attention (Taylor and Thoroughman, 2007; Anguera et al., 2010).

In visuomotor adaptation research domain, several inadequacies were detected both based on the types of tasks utilized and the measurements taken during this process. Regarding changes in eye-hand coordination and hemodynamic response during visuomotor adaptation, the limited point of view provided by various studies was emphasized in terms of their reliance on traditional trajectory manipulations and their ability to only account for the changes in these measurements during a traditional visuomotor rotation trajectory. Previous studies conducted to investigate the changes in eye-hand coordination supplied valuable information related to

adaptation to a visuomotor rotation manipulation or the role of visual guidance during adaptation takes place which were described in more detail in the introduction section. Abrams and colleagues (1990) focused on and emphasized the essential role of visual guidance during visuomotor adaptation and suggested that absence of visual guidance deteriorated performance. The trajectory manipulations in all three studies stated above were linear trajectory manipulation even though the degree of manipulation were occasionally various. Sailer and colleagues (2005) revealed the process by which the eye moves from the guiding organ to being a playing a more predictive role to locate the next target as adaptation occurs however; owing to its complexity, generalizability of their task was criticized by Rentsch and Rand (2014), who utilized a simpler traditional task and demonstrated how multiple angles of rotation manipulation would influence changes in eye-hand coordination and stated that the guidance provided by the eye to hand decreased with practice related to the presented task. However; the focus on generalizability shadowed the possibility of exploring new trajectory manipulations and probable changes in eye-hand coordination in adaptation to novel visuomotor mapping rules. Moreover; visual guidance provided by the eye to manual movements was not investigated for real trajectory manipulation since studies conducted in this field examined eye-hand coordination during the visual feedback was manipulated, not the cursor itself. The case was similar in neural correlates of visuomotor rotation since the applied trajectory manipulations were counter-clockwise or clockwise linear rotation (Gentili and colleagues 2008, 2010; Anguera and colleagues 2010). Furthermore; though Gentili and colleagues (2008, 2010) revealed significant changes in prefrontal cortex activity during visuomotor adaptation task; since they required participants to select one target at a time, which resulted in carrying the behavior to conscious level while visuomotor adaptation is a more unconscious process (Willingham, 1998).

The present study, therefore; contributed to visuomotor adaptation research domain in not only providing an alternative to traditionally applied linear trajectory manipulation but also a comparative analysis between linear trajectory manipulation and non-linear/circular trajectory manipulation based on changes in reaction time, eye-hand coordination and hemodynamic response throughout the adaptation process. Unlike previous studies the main focus of this study was not to examine generalization that occurs during visuomotor adaptation or error detection, on the

113

contrary, a comprehensive analysis for separate trajectory manipulations was conducted. Hence, this study did not remain with a limited understanding of the amount of information provided by linear trajectory manipulation and its previously investigated effects on reaction time, visual guidance for manual movements and hemodynamic response changes. The influences that might result from intervening neural activities such as target-selection were avoided and adaptation process was maintained as unconscious as possible by implicit learning strategies. A thorough analysis including local components of eye-hand coordination was provided for a genuine rotation manipulation rather than rotated visual feedback and therefore, revealed the changes related to visual guidance when participants literally performed this trajectory manipulation with initiating manual movements.

To conclude; in the current study, regarding the analysis conducted on gradual changes in reaction time, eye-hand coordination and hemodynamic response, the significant influence of the presented type of trajectory manipulation was demonstrated. The relatively higher task difficulty of circular visuomotor rotation task over linear visuomotor rotation task was supported by either a significant main effect condition on overall changes in reaction time, eye-hand coordination and hemodynamic response or a significant interaction effect between condition and gradual changes in these measurements throughout trials. Significant differences observed between circular visuomotor rotation task and traditional visuomotor rotation task based on eye-hand coordination and hemodynamic response consistently indicated a more difficult adaptation process to circular visuomotor rotation compared to traditional visuomotor rotation and also the fact that without the necessity for a highly complex task to observe changes in visual guidance, a modification on a simple task was also sufficient to enlighten novel trajectory adaptation processes. Plus, this study confirmed and further supported the effective utilization of *f*NIR in recording and examining hemodynamic response produced during visuomotor adaptation. In addition to these, the current study, as far as it is known, is the first study to investigate the changes in eye-hand coordination and hemodynamic response during adaptation to circular rotation manipulation occurred and also the first study to provide a comparative analysis between a traditional trajectory manipulation and a novel trajectory manipulation.

4.5. Limitations and Future Directions

Some limitations were encountered during the conductance of this study. First one is related to the difficulty of obtaining high quality neural data, owing to sensitivity of *f*NIR device to hair, skin color and thickness of skull. This sensitivity resulted in excluding some of the participants from the analysis. Second is related to calibration phase of eye-tracking which necessitated participants' eyes to be highly correlated with dots presented on screen on both x and y axes and participants who failed to calibrate were not allowed in the study. The last limitation was related to the failure to measure cortical activities in other regions of the brain in addition to prefrontal cortex. Such ability would enable an investigation related to all phases of visuomotor adaptation since activity in prefrontal cortex occurs during early stages of motor learning. Therefore; the shift from frontal areas to temporal and parietal cortices could have been thoroughly examined.

Regarding the future applications of this study, researchers may include additional number of trials to investigate later phases of visuomotor adaptation to novel (circular) visuomotor rotation regarding changes in eye-hand coordination and hemodynamic correlates. However, the effects of fatigue should be controlled as it would be difficult to differentiate between the shift of activity from frontal areas to parietal and temporal areas from decreased activity resulting from the influence of fatigue. Additionally, the effects of fatigue can be observed in eye-hand coordination as well. Following the early stages, eye and hand might be completely uncoupled due to fatigue or successful adaptation to visuomotor rotation. In summary, it might be useful to present more visuomotor rotation trials; however, distinguishing between real effects and effects of fatigue might be problematic.

Additionally, in order to determine whether linear trajectory manipulation and circular visuomotor trajectory manipulation are saved and utilized by the same internal model, a within-design study can be conducted with counterbalancing the appearance of conditions. As it was suggested in a study conducted by Wigmore and colleagues (2002), participants forgot what they learned in a specific trajectory manipulation after they were asked to adapt to an altered degree of trajectory manipulation. The authors of the study concluded that trajectory manipulation was represented by a single internal model. However; they only utilized linear trajectory

manipulation and therefore whether linear and circular trajectory manipulations are represented by the same internal model still remains unclear.

Moreover; simultaneous measurement of visual data and hemodynamic response can be carried out. This might be more advantageous as the sample will consist of same participants. Recruiting the same participants was avoided in this study as prefrontal cortex is involved in early stages of learning and participants who previously trained with the task and environment in Study 1 would transfer the outcomes of this experience to Study 2, which would eliminate the possibility of measuring hemodynamic response in early stages. Additionally, a thorough and united analysis of the process related to guidance of visual information and underlying neural processes can be provided with this method.

<div align="center">**References**</div>

Abrams, R. A., Meyer, D. E., & Kornblum, S. (1990). Eye-hand coordination: oculomotor control in rapid aimed limb movements. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(2), 248-267.

Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior*, *3*(2), 111-150.

Anguera, J. A., Reuter-Lorenz, P. A., Willingham, D. T., & Seidler, R. D. (2010). Contributions of spatial working memory to visuomotor learning. *Journal of Cognitive Neuroscience*, *22*(9), 1917-1930.

Anguera, J. A., Russell, C. A., Noll, D. C., & Seidler, R. D. (2007). Neural correlates associated with intermanual transfer of sensorimotor adaptation. *Brain Research*, *1185*, 136-151.

Ayaz, H., Izzetoglu, M., Shewokis, P. A., & Onaral, B. (2010, August). Sliding-window motion artifact rejection for functional near-infrared spectroscopy. *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE* (pp. 6567-6570). IEEE.

Ayaz, H., Shewokis, P. A., Bunce, S., Izzetoglu, K., Willems, B., & Onaral, B. (2012). Optical brain monitoring for operator training and mental workload assessment. *Neuroimage*, *59*(1), 36-47.

Ayaz, H., Shewokis, P. A., Curtin, A., Izzetoglu, M., Izzetoglu, K., & Onaral, B. (2011). Using MazeSuite and functional near infrared spectroscopy to study learning in spatial navigation. *JoVE (Journal of Visualized Experiments)*, (56), e3443, doi: 10.3791/3443.

Baker, W. B., Parthasarathy, A. B., Busch, D. R., Mesquita, R. C., Greenberg, J. H., & Yodh, A. G. (2014). Modified Beer-Lambert law for blood flow. *Biomedical Optics Express*, *5*(11), 4053-4075.

Baldwin, S. A., & Hoffmann, J. P. (2002). The dynamics of self-esteem: A growth-curve analysis. *Journal of Youth and Adolescence*, *31*(2), 101-113.

Bates, D., Kliegl, R., Vasishth, S., & Baayen, H. (2015). Parsimonious mixed models. *arXiv preprint.* 1-27. *arXiv:1506.04967*.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B (Methodological)*, *57*(1) 289-300.

Berry, D., & Dienes, Z. P. (1993). *Implicit learning: Theoretical and empirical issues*. Essays in cognitive psychology. Lawrence Erlbaum Associates, Hove, pp197. ISBN 0863772234

Blake, L., Craven, M., Dobell, D., Flood, N., Jasper, G., Little, … & Price, G. (2002). In The Nervous System. J. Bocknek, A. Drabyk, D. Kozlovic, L. McKarney, F. Purslow, N. Purslow, T. Shields, M. J., Webb (Eds.). *Biology 12* (12th ed., pp. 136-163). Toronto: McGraw-Hill Ryerson.

Bock, O., Thomas, M., & Grigorova, V. (2005). The effect of rest breaks on human sensorimotor adaptation. *Experimental Brain Research*, *163*(2), 258-260. Borsa, P. A.,

Bowman, M. C., Johannson, R. S., & Flanagan, J. R. (2009). Eye–hand coordination in a sequential target contact task. *Experimental Brain Research*, *195*(2), 273-283.

Bradberry, T. J., Gentili, R. J., & Contreras-Vidal, J. L. (2010). Reconstructing three-dimensional hand movements from noninvasive electroencephalographic signals. *Journal of Neuroscience*, *30*(9), 3432-3437.

Brain Facts: A Primer On The Brain And Nervous System, Society for Neuroscience, www.sfn.org, 2006 (www.sfn.org/skins/main/pdf/brainfacts/brainfacts.pdf).

Brooks, R., & Meltzoff, A. N. (2008). Infant gaze following and pointing predict accelerated vocabulary growth through two years of age: A longitudinal, growth curve modeling study. *Journal of Child Language*, *35*(01), 207-220.

Buch, E. R., Young, S., & Contreras-Vidal, J. (2003). Visuomotor adaptation in normal aging. *Learning & Memory, 10*(1), 55-63. doi: http://dx.doi.org/10.1101/lm.50303

Bund, A., & Wiemeyer, J. (2004). Self-controlled learning of a complex motor skill: Effects of the learners' preferences on performance and self-efficacy. *Journal of Human Movement Studies*, *47*(3), 215-236.

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience*, *12*(1), 1-47.

Caithness, G., Osu, R., Bays, P., Chase, H., Klassen, J., Kawato, M., … & Flanagan, J. R. (2004). Failure to consolidate the consolidation theory of learning for sensorimotor adaptation tasks. *Journal of Neuroscience*, *24*(40), 8662-8671.

Calton, J. L., Dickinson, A. R., & Snyder, L. H. (2002). Non-spatial, motor-specific activation in posterior parietal cortex. *Nature Neuroscience*, *5*(6), 580-588.

Chase, S. M., Kass, R. E., & Schwartz, A. B. (2012). Behavioral and neural correlates of visuomotor adaptation observed through a brain-computer interface in primary motor cortex. *Journal of Neurophysiology*, 108(2), 624-644.

Chiodi, S. N. (2013). *Growth Curve Models for Longitudinal Data: Application for Psychiatric Research* (Doctoral dissertation, Emory University).

Crawford, J. D., Medendorp, W. P., & Marotta, J. J. (2004). Spatial transformations for eye–hand coordination. *Journal of Neurophysiology*, *92*(1), 10-19.

Crossman, E. R. F. W., & Goodeve, P. J. (1983). Feedback control of hand-movement and Fitts' law. *The Quarterly Journal of Experimental Psychology*, *35*(2), 251-278.

Cui, X., Bray, S., & Reiss, A. L. (2010). Functional near infrared spectroscopy (NIRS) signal improvement based on negative correlation between oxygenated and deoxygenated hemoglobin dynamics. *Neuroimage*, *49*(4), 3039-3046.

Cunningham, H. A. (1989). Aiming error under transformed spatial mappings suggests a structure for visual-motor maps. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(3), 493.

Curran, P. J., Obeidat, K., & Losardo, D. (2010). Twelve frequently asked questions about growth curve modeling. *Journal of Cognition and Development*, *11*(2), 121-136.

Curran, T., & Keele, S. W. (1993). Attentional and nonattentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*(1), 189-202.

Davidson, R. J., & Sutton, S. K. (1995). Affective neuroscience: The emergence of a discipline. *Current Opinion in Neurobiology*, *5*(2), 217-224.

Deiber, M. P., Wise, S. P., Honda, M., Catalan, M. J., Grafman, J., & Hallett, M. (1997). Frontal and parietal networks for conditional motor learning: a positron emission tomography study. *Journal of Neurophysiology*, *78*(2), 977-991.

Disbrow, E. A., Slutsky, D. A., Roberts, T. P., & Krubitzer, L. A. (2000). Functional MRI at 1.5 tesla: a comparison of the blood oxygenation level-dependent signal and electrophysiology. *Proceedings of the National Academy of Sciences*, *97*(17), 9718-9723.

Doyon, J., Owen, A. M., Petrides, M., Sziklas, V., & Evans, A. C. (1996). Functional anatomy of visuomotor skill learning in human subjects examined with positron emission tomography. *European Journal of Neuroscience*, *8*(4), 637-648.

Ebbinghaus, H. (2013). Memory: a contribution to experimental psychology. *Annals of Neurosciences*, *20*(4), 155-156.

Edwards, W. (2011). *An introduction to motor learning and motor control*. Pacific Grove, Calif.: Wadsworth ; Andover: Cengage Learning [distributor].

Fernandez-Ruiz, J., Wong, W., Armstrong, I. T., & Flanagan, J. R. (2011). Relation between reaction time and reach errors during visuomotor adaptation. *Behavioral Brain Research*, *219*(1), 8-14.

Field, A. P., Miles, J., & Field, Z. (2012). *Discovering statistics using R* (p. 995). London: Sage.

Fischer, M. H., Pratt, J., & Neggers, S. F. (2003). Inhibition of return and manual pointing movements. *Perception & Psychophysics*, *65*(3), 379-387.

Flanders, M., Tillery, S. I. H., & Soechting, J. F. (1992). Early stages in a sensorimotor transformation. *Behavioral and Brain Sciences*, *15*(02), 309-320.

Floyer-Lea, A., & Matthews, P. M. (2004). Changing brain networks for visuomotor control with increased movement automaticity. *Journal of Neurophysiology*, *92*(4), 2405-2412.

Francis, J. T. (2005). Influence of the inter-reach-interval on motor learning. *Experimental Brain Research*, *167*(1), 128-131.

Frensch, P. A. (1998). Same concept, multiple meanings: On how to define the concept of implicit learning. In M. Stadler & P. A. Frensch (Eds.), *Handbook of implicit learning* (pp. 47-104). Thousand Oaks, CA: Sage

Gatti, R., Tettamanti, A., Gough, P. M., Riboldi, E., Marinoni, L., & Buccino, G. (2013). Action observation versus motor imagery in learning a complex motor task: a short review of literature and a kinematics study. *Neuroscience Letters*, *540*, 37-42.

Gaveau, V., Pélisson, D., Blangero, A., Urquizar, C., Prablanc, C., Vighetto, A., & Pisella, L. (2008). Saccade control and eye–hand coordination in optic ataxia. *Neuropsychologia*, *46*(2), 475-486.

Gentili, R. J., Bradberry, T. J., Hatfield, B. D., & Contreras-Vidal, J. L. (2008, August). A new generation of non-invasive biomarkers of cognitive-motor states with application to smart brain-computer interfaces. *Signal Processing Conference, 2008 16th European* (pp. 1-5). IEEE.

Gentili, R. J., Hadavi, C., Ayaz, H., Shewokis, P. A., & Contreras-Vidal, J. L. (2010, August). Hemodynamic correlates of visuomotor motor adaptation by functional near infrared spectroscopy. *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE* (pp. 2918-2921). IEEE.

Goldman-Rakic, P.S. (1987). Circuitry of primate prefrontal cortex and regulation of behavior by representational memory. In F. Plum (Ed.), *Handbook of Physiology*: The nervous system (pp. 373-401). Bethesda, MD: American Physiological Society.

Grimm, K. J., Ram, N., & Hamagami, F. (2011). Nonlinear growth curves in developmental research. *Child Development*, *82*(5), 1357-1371.

Halsband, U., & Lange, R. K. (2006). Motor learning in man: a review of functional and clinical studies. *Journal of Physiology-Paris*, *99*(4), 414-424.

Hayes, N. A., & Broadbent, D. E. (1988). Two modes of learning for interactive tasks. *Cognition*, *28*(3), 249-276.

Heilbronner, U., Hinrichs, H., Heinze, H. J., & Zaehle, T. (2015). Caffeine differentially alters cortical hemodynamic activity during working memory: a near infrared spectroscopy study. *BMC research notes*, *8*(1), 520.

Hill, A. L. (1972). Direction constancy. *Attention, Perception, & Psychophysics*, *11*(2), 175-178.

Hinder, M. R., Woolley, D. G., Tresilian, J. R., Riek, S., & Carson, R. G. (2008). The efficacy of colour cues in facilitating adaptation to opposing visuomotor rotations. *Experimental Brain Research*, *191*(2), 143-155.

Imamizu, H., Miyauchi, S., Tamada, T., Sasaki, Y., Takino, R., PuÈtz, B., … & Kawato, M. (2000). Human cerebellar activity reflecting an acquired internal model of a new tool. *Nature*, *403*(6766), 192-195.

Izzetoglu, M., Izzetoglu, K., Bunce, S., Ayaz, H., Devaraj, A., Onaral, B., & Pourrezaei, K. (2005). Functional near-infrared neuroimaging. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *13*(2), 153-159.

James, W. (1950). *The Principles of Psychology* (Vol. 2). New York: Dover Publications. (Original work published 1890)

Janelle, C. M., Barba, D. A., Frehlich, S. G., Tennant, L. K., & Cauraugh, J. H. (1997). Maximizing performance feedback effectiveness through videotape replay and a self-controlled learning environment. *Research Quarterly for Exercise and Sport*, *68*(4), 269-279.

Johansson, R. S., Westling, G., Bäckström, A., & Flanagan, J. R. (2001). Eye–hand coordination in object manipulation. *Journal of Neuroscience*, *21*(17), 6917-6932.

Kagerer, F. A., Contreras-Vidal, J. L., & Stelmach, G. E. (1997). Adaptation to gradual as compared with sudden visuo-motor distortions. *Experimental Brain Research*, *115*(3), 557-561.

Karni, A. (1996). The acquisition of perceptual and motor skills: a memory system in the adult human cortex. *Cognitive Brain Research*, *5*(1), 39-48.

Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, *9*(6), 718-727.

Keele, S. W., & Posner, M. I. (1968). Processing of visual feedback in rapid movements. *Journal of Experimental Psychology*, *77*(1), 155.

Kerr, B. (1978). Task factors that influence selection and preparation for voluntary movements. In G. E. Stelmach (Ed.), *Information Processing in Motor Control and Learning* (pp. 55-69). New York: Academic Press.

Klassen, J., Tong, C., & Flanagan, J. R. (2005). Learning and recall of incremental kinematic and dynamic sensorimotor transformations. *Experimental Brain Research*, *64*(2), 250-259.

Kording, K. P., Tenenbaum, J. B., & Shadmehr, R. (2007). The dynamics of memory as a consequence of optimal adaptation to a changing body. *Nature Neuroscience*, *10*(6), 779-786.

Krakauer, J. W. (2006). Motor learning: its relevance to stroke recovery and neurorehabilitation. *Current Opinion in Neurology*, *19*(1), 84-90.

Krakauer, J. W. (2009). Motor learning and consolidation: the case of visuomotor rotation. *Progress in Motor Control* (pp. 405-421). Springer US.

Krakauer, J. W., Ghez, C., & Ghilardi, M. F. (2005). Adaptation to visuomotor transformations: consolidation, interference, and forgetting. *Journal of Neuroscience*, *25*(2), 473-478.

Krakauer, J. W., Ghilardi, M. F., Mentis, M., Barnes, A., Veytsman, M., Eidelberg, D., & Ghez, C. (2004). Differential cortical and subcortical activations in learning rotations and gains for reaching: a PET study. *Journal of Neurophysiology*, *91*(2), 924-933.

Krakauer, J. W., Pine, Z. M., Ghilardi, M. F., & Ghez, C. (2000). Learning of visuomotor transformations for vectorial planning of reaching trajectories. *Journal of Neuroscience*, *20*(23), 8916-8924.

Lackner, J. R., & Dizio, P. (1994). Rapid adaptation to Coriolis force perturbations of arm trajectory. *Journal of Neurophysiology*, *72*(1), 299-313.

Lephart, S. M., Irrgang, J. J., Safran, M. R., & Fu, F. H. (1997). The effects of joint position and direction of joint motion on proprioceptive sensibility in anterior cruciate ligament-deficient athletes. *The American Journal of Sports Medicine*, *25*(3), 336-340.

Levy, B. J., & Wagner, A. D. (2011). Cognitive control and right ventrolateral prefrontal cortex: reflexive reorienting, motor inhibition, and action updating. *Annals of the New York Academy of Sciences*, *1224*(1), 40-62.

Liang, L. Y., Shewokis, P. A., & Getchell, N. (2016). Brain Activation in the Prefrontal Cortex during Motor and Cognitive Tasks in Adults. *Journal of Behavioral and Brain Science*, *6*(12), 463.

Liao, L. D., Tsytsarev, V., Delgado-Martínez, I., Li, M. L., Erzurumlu, R., Vipin, A., ... & Thakor, N. V. (2013). Neurovascular coupling: in vivo optical techniques for functional brain imaging. *Biomedical Engineering Online*, *12*(1), 38.

Lin, J. H., Saito, T., Anderson, D. J., Lance-Jones, C., Jessell, T. M., & Arber, S. (1998). Functionally related motor neuron pool and muscle sensory afferent subtypes defined by coordinate ETS gene expression. *Cell*, *95*(3), 393-407.

Marieb, E. N., Hoehn, K., & Hutchinson, Matt, (2013). *Human anatomy & physiology* (9th edition). [San Francisco] Pearson Education/Benjamin Cummings.

Mazzoni, P., & Krakauer, J. W. (2006). An implicit plan overrides an explicit strategy during visuomotor adaptation. *Journal of Neuroscience*, *26*(14), 3642-3645.

McKendrick, R., Ayaz, H., Olmstead, R., & Parasuraman, R. (2014). Enhancing dual-task performance with verbal and spatial working memory training: continuous monitoring of cerebral hemodynamics with NIRS. *Neuroimage*, *85*, 1014-1026.

Meece, J. L. (1994). The role of motivation in self-regulated learning. In D. Schunk & B. Zimmerman (Eds.), *Self-regulation of Learning and Performance: Issues and Educational Applications* (pp. 25-44). Hillsdale, NJ: Erlbaum.

Meredith, W., & Tisak, J. (1990). Latent curve analysis. *Psychometrika*, *55*(1), 107-122.

Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Keith Smith, J. E. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review*, *95*(3), 340.

Meyer, D. E., Smith, J. E. K., Kornblum, S., Abrams, R. A., & Wright, C. E. (1990). Speed-accuracy tradeoffs in aimed movements: Toward a theory of rapid voluntary action. In M. Jeannerod (Ed.), *Attention and Performance XIII* (pp. 173-226). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Miall, R. C., Reckess, G. Z., & Imamizu, H. (2001). The cerebellum coordinates eye and hand tracking movements. *Nature Neuroscience*, *4*(6), 638-644.

Mirman, D. (2014). When change over time is not linear. In J. M. Chambers, T. Hothorn, D. T. Lang, H. Wickham (Eds.) *Growth curve analysis and visualization using R* (p. 168). Boca Raton, FL: CRC Press.

Morgan, C. L. (1978). Constancy of egocentric visual direction. *Attention, Perception, & Psychophysics*, *23*(1), 61-68.

Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. *Cognitive Skills and Their Acquisition*, *1*, 1-55.

Nordenberg, D., Yip, R., & Binkin, N. J. (1990). The effect of cigarette smoking on hemoglobin levels and anemia screening. *Jama*, *264*(12), 1556-1559.

Nourouzpour, N., Salomonczyk, D., Cressman, E. K., & Henriques, D. Y. (2015). Retention of proprioceptive recalibration following visuomotor adaptation. *Experimental Brain Research*, *233*(3), 1019-1029.

O'Brien, S. (2009). Eye tracking in translation process research: methodological challenges and solutions. *Methodology, Technology and Innovation in Translation Process Research*, *38*, 251-266.

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

Petersen, S. E., Corbetta, M., Miezin, F. M., & Shulman, G. L. (1994). PET studies of parietal involvement in spatial attention: comparison of different task types. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *48*(2), 319-338.

Prablanc, C., Echallier, J. F., Komilis, E., & Jeannerod, M. (1979). Optimal response of eye and hand motor systems in pointing at a visual target: I. Spatio-temporal characteristics of eye and hand movements and their relationships when

varying the amount of visual information. *Biological Cybernetics*, *35*(2), 113-124.

Rahman, M. A., & Ahmad, M. (2016, December). Movement related events classification from functional near infrared spectroscopic signal. *Computer and Information Technology (ICCIT), 2016 19th International Conference on* (pp. 207-212). IEEE.

Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General*, *118*(3), 219.

Rentsch, S., & Rand, M. K. (2014). Eye-hand coordination during visuomotor adaptation with different rotation angles. *PloS one*, *9*(10), e109819.

Ryan, R. M., & Deci, E. L. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. *Contemporary Educational Psychology*, *25*(1), 54-67.

Sailer, U., Flanagan, J. R., & Johansson, R. S. (2005). Eye–hand coordination during learning of a novel visuomotor task. *Journal of Neuroscience*, *25*(39), 8833-8842.

Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: a review and critical reappraisal. *Psychological Bulletin*, *95*(3), 355.

Schaffert, J. (2014). *Visuomotor Adaptation in Older Adults with and without Cognitive Impairment*. (Doctoral dissertation, Eastern Michigan University).

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, *82*(4), 225.

Schmidt, R. A. (1991). Frequent augmented feedback can degrade learning: Evidence and interpretations. *Tutorials in Motor Neuroscience* (pp. 59-75). Springer Netherlands.

Seidler, R. D. (2010). Neural correlates of motor learning, transfer of learning, and learning to learn. *Exercise and Sport Sciences Reviews*, *38*(1), 3.

Seidler, R. D., & Noll, D. C. (2008). Neuroanatomical correlates of motor acquisition and motor transfer. *Journal of Neurophysiology*, *99*(4), 1836-1845.

Seidler, R.D., Noll, D.C., Chintalapati, P., 2006. Bilateral basal ganglia activation associated with sensorimotor adaptation. *Experimental Brain Research*. 175 (3), 544–555.

Sela, I., Horowitz–Kraus, T., Izzetoglu, M., Shewokis, P. A., Izzetoglu, K., Onaral, B., & Breznitz, Z. (2011). Brain activity of young and adult hebrew speakers during lexical decision task: FNIR application to language. *International Conference on Foundations of Augmented Cognition* (pp. 231-239). Springer Berlin Heidelberg.

Sela, I., Izzetoglu, M., Izzetoglu, K., & Onaral, B. (2012). A working memory deficit among dyslexic readers with no phonological impairment as measured using the N-Back task: An fNIR study. *PloS one*, *7*(11), e46527.

Shadmehr, R., & Holcomb, H. H. (1997). Neural correlates of motor memory consolidation. *Science*, *277*(5327), 821-825.

Smith, M. A., Ghazizadeh, A., & Shadmehr, R. (2006). Interacting adaptive processes with different timescales underlie short-term motor learning. *PLoS Biology*, *4*(6), e179.

Steinman, R.M., 2003. Gaze control under natural conditions. In Chalupa, L.M., Werner, J.S. (Eds.), *The Visual Neurosciences* (pp. 1339–1356). MIT Press, Cambridge MA.

Strangman, G., Culver, J. P., Thompson, J. H., & Boas, D. A. (2002). A quantitative comparison of simultaneous BOLD fMRI and NIRS recordings during functional brain activation. *Neuroimage*, *17*(2), 719-731.

Sulzer-Azaroff, B., & Mayer, G. R. (1991). In G. R. Mayer (Ed.), *Behavior analysis for lasting change* (p. 644). Holt, Rinehart & Winston.

Tanji, J., & Hoshi, E. (2001). Behavioral planning in the prefrontal cortex. *Current Opinion in Neurobiology*, *11*(2), 164-170.

Taylor, J. A., & Thoroughman, K. A. (2007). Divided attention impairs human motor adaptation but not feedback control. *Journal of Neurophysiology*, *98*(1), 317-326.

Théau, J. (2008). Temporal Resolution. In *Encyclopedia of GIS* (pp. 1150-1151). Springer US.

Ungerleider, L. G., Doyon, J., & Karni, A. (2002). Imaging brain plasticity during motor skill learning. *Neurobiology of Learning and Memory*, *78*(3), 553-564.

Urie, B. (1981). The ecology of human development: Experiments by nature and design. *The Journal of Mind and Behavior, 3*(2), 365-369.

Von Hofsten, C. (1982). Eye–hand coordination in the newborn. *Developmental Psychology*, *18*(3), 450-461.

Wallace, S. A., & Newell, K. M. (1983). Visual control of discrete aiming movements. *The Quarterly Journal of Experimental Psychology*, *35*(2), 311-321.

Wigmore, V., Tong, C., & Flanagan, J. R. (2002). Visuomotor rotations of varying size and direction compete for a single internal model in a motor working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(2), 447-457.

Willingham, D. B. (1998). A neuropsychological theory of motor skill learning. *Psychological Review*, *105*(3), 558-584.

Winter, D. A. (1990) *Biomechanics and Motor Control of Human Movement*, (2nd Ed.) (pp. 41–45). New York: Wiley.

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. *Nature Reviews Neuroscience*, *12*(12), 739-751.

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, *269*(5232), 1880-1882.

Woodworth, R. S. (1899). The Accuracy Of Voluntary Movement. *The Journal of Nervous and Mental Disease*, *26*(12), 743-752.

Wray, S., Cope, M., and Delpy, D. T. 1988. Characteristics of the near infrared absorption spectra of cytochrome aa3 and hemoglobin for the noninvasive monitoring of cerebral oxygenation. *Biochimica et Biophysica Acta. 933*, 184–192.

APPENDIX A

"Participant Information Form" presented to participants prior to experiment for Study 1 and Study 2.

KATILIMCI BİLGİLENDİRME FORMU 1. Çalışma

Bu çalışmanın amacı, yeni bir görsel-motor rotasyon görevine uyum süreçlerinde göz-el koordinasyonuna ilişkin değişimlerin incelenmesidir.

Çalışmaya başlamadan önce araştırmacı sizden bir takım soruları yanıtlamanızı isteyecek ve ardından sizi deneysel oturumun gerçekleşeceği odaya alacaktır. Deney süresince başınızı mümkün olduğu kadar sabit tutmanız ve gözlerinizi bilgisayar ekranından hiç ayırmamanız beklenmektedir. Çalışma boyunca, ekrandan sunulan yönergeleri dikkatlice okumanız ve sizden istenenleri olabildiğince doğru bir biçimde yerine getirmeniz gerekmektedir.

Çalışma kapsamında katılımcılardan elde edilen veriler isim kullanılmaksızın analizlere dâhil edilecektir. Çalışma başında size bir katılımcı numarası verilecek ve isminiz araştırma raporunda yer almayacaktır.

Katılımınız araştırma hipotezinin test edilmesi ve yukarıda açıklanan amaçlar doğrultusunda literatüre sağlayacağı katkılar bakımından oldukça önemlidir. Ayrıca katılımınızın psikoloji alanın gelişmesi açısından da bir takım faydaları bulunmaktadır. Çalışmaya katılmanız tamamen kendi isteğinize bağlıdır. Katılımı reddetme ya da çalışma sürecinde herhangi bir zaman diliminde devam etmeme hakkına sahipsiniz. Eğer görüşme esnasında katılımınıza ilişkin herhangi bir sorunuz olursa, araştırmacıyla iletişime geçebilirsiniz.

Bu çalışmanın amacı, yeni bir görsel-motor rotasyon görevine uyum süreçlerinde beyinde meydana gelen hemodinamik aktivite değişikliklerinin incelenmesidir. Çalışmaya başlamadan önce araştırmacı sizden bir takım soruları yanıtlamanızı isteyecek ve ardından sizi deneysel oturumların gerçekleşeceği odaya alacaktır. Bu odadaki koltukta rahat bir pozisyonda oturmanız, uygulamalar boyunca konuşmamanız ve pozisyonunuzu korumanız çalışmanın başarısı açısından oldukça önemlidir. Araştırmacı ön beyin aktivitesini takip etmek amacıyla alın bölgenize bir bant yerleştirecektir. Bu işlem bittikten sonra araştırmacı yanınızdan ayrılıp yan odada sizi bekliyor olacaktır. Çalışma boyunca, ekrandan sunulan yönergeleri dikkatlice okumanız ve sizden istenenleri olabildiğince doğru bir biçimde yerine getirmeniz gerekmektedir.

Çalışma kapsamında katılımcılardan elde edilen veriler isim kullanılmaksızın analizlere dâhil edilecektir. Çalışma başında size bir katılımcı numarası verilecek ve isminiz araştırma raporunda yer almayacaktır. Katılımınız araştırma hipotezinin test edilmesi ve yukarıda açıklanan amaçlar doğrultusunda literatüre sağlayacağı katkılar bakımından oldukça önemlidir. Ayrıca katılımınızın psikoloji alanın gelişmesi açısından da bir takım faydaları bulunmaktadır. Çalışmaya katılmanız tamamen kendi isteğinize bağlıdır. Katılımı reddetme ya da çalışma sürecinde herhangi bir zaman diliminde devam etmeme hakkına sahipsiniz. Eğer görüşme esnasında katılımınıza ilişkin herhangi bir sorunuz olursa, araştırmacıyla iletişime geçebilirsiniz.

APPENDIX B

"Informed Consent form" presented to participants prior to experiment.

KATILIMCI İZİN FORMU

Çalışmanın amacını ve içeriğini .... katılımcı numarasına sahip katılımcıya açıklamış bulunmaktayım. Çalışma kapsamında yapılacak işlemler hakkında katılımcının herhangi bir sorusu olup olmadığını sordum ve katılımcı tarafından yöneltilen bütün soruları yanıtladım.

Tarih: Araştırmacının İmzası:

..... / ..... / ....

....

Çalışmanın amacı ve içeriği hakkında açıklamaların yer aldığı Katılımcı Bilgilendirme Formu'nu okudum. Araştırmacı çalışma kapsamındaki haklarımı ve sorumluluklarımı açıkladı ve kendisine yönelttiğim bütün soruları açık bir şekilde yanıtladı. Sonuç olarak, uygulama esnasında şahsımdan toplanan verilerin bilimsel amaçlarla kullanılmasına izin verdiğimi ve çalışmaya gönüllü olarak katıldığımı beyan ederim.

Tarih: Katılımcının İmzası:

..... / ..... / ....

....

131

"Participant Evaluation Form" presented to participants prior to experiment.

KATILIMCI BİLGİ FORMU

AD-SOYAD:	TELEFON NUMARASI:
CİNSİYET:	e-MAIL:
YAŞ:	OKUL:
MESLEK:	

Aşağıdaki soruları yanıtlarken size en uygun olan numarayı yuvarlak içine alınız.

(0= hiç yorgun değil, 7= çok yorgun)

1. Şu anda kendinizi ne kadar yorgun hissediyorsunuz?

0 -----1 -----2 -----3 -----4 -----5 -----6 -----7

Aşağıdaki soruları yanıtlarken lütfen durumunuzu en iyi yansıtan seçeneği işaretleyiniz.

1. Yakın zamanda (son 1 sene dahil) başka bir psikoloji deneyine katıldınız mı?

○ Evet   ○ Hayır

Yanıtınız "Evet" ise 2.sorudan, "Hayır" ise 3. sorudan devam ediniz.

2. Hangi deneye katıldınız?

…………………………………………………………………………………………
……….......

3. Herhangi ciddi bir görme bozukluğunuz var mı?

○ Evet   ○ Hayır

4. Herhangi bir psikolojik rahatsızlık geçmişiniz var mı?

○ Evet   ○ Hayır

Yanıtınız "Evet" ise 5. sorudan, "Hayır" ise 7. sorudan devam ediniz.

5. Bir ruh sağlığı çalışanı tarafından rahatsızlığınıza konulan tanı nedir?

…………………………………………………………………………………………

………

6. Rahatsızlığınız ile ilgili kullandığınız ilaç(lar) var mı?

     ○ Evet,……………………………………………isimli ilaç(lar)ı kullandım/kullanmaktayım.

     ○ Hayır

7. Herhangi bir nörolojik hastalık geçmişiniz var mı?

     ○ Evet   ○ Hayır

Yanıtınız "Evet" ise 8. sorudan, "Hayır" ise 10. sorudan devam ediniz.

8. Bir uzman tarafından hastalığınıza konulan tanı nedir?

………………………………………………………………………………………………
……

9. Hastalığınız ile ilgili kullandığınız ilaç(lar) var mı?

     ○ Evet,……………………………………isimli ilaç(lar)ı kullandım/kullanmaktayım.

     ○ Hayır

10. Daha önce kafa travması geçirdiniz mi?

     ○ Evet   ○ Hayır

11. Düzenli olarak kullandığınız ilaç(lar) var mı?

     ○ Evet   ○ Hayır

Yanıtınız "Evet" ise 12. sorudan, "Hayır" ise 13. sorudan devam ediniz.

12. Lütfen kullandığınız ilaç(lar)ı ve ilaç(lar)ın kullanım amaçlarını belirtiniz.

İlaç(lar):………………….……..….……..… Kullanım

amacı:………….……..………………

13. Herhangi bir kalp rahatsızlığı tanısı aldınız mı?

     ○ Evet   ○ Hayır

Yanıtınız "Evet" ise 14. sorudan, "Hayır" ise 15. sorudan devam ediniz.

14. Size konulan tanıyı belirtiniz.

………………………………………………………………………………………………

………........

15. Herhangi bir ameliyat/ operasyon geçirdiniz mi?

○ Evet   ○ Hayır

Yanıtınız "Evet" ise 16. sorudan, "Hayır" ise 17. sorudan devam ediniz.

16. Geçirdiğiniz ameliyatı/operasyonu lütfen belirtiniz.

Ameliyat/operasyon:……….…… Ameliyat/operasyon

tarihi:…………………

17. Dün akşam kaç saat uyudunuz?

○ 5 saatten az   ○ 6-8 saat   ○ 8 saatten fazla

18. Aneminiz (kansızlığınız) var mı?

○ Evet   ○ Hayır

APPENDIX D

"Edinburg's Handedness Inventory" presented to participants prior to experiment.

Edinburgh El Tercihi Envanteri					
	Her zaman sol	Genelde sol	Tercihim yok	Genelde sağ	Her zaman sağ
Yazma					
Fırlatma					
Makas					
Diş fırçası					
Bıçak					
Kaşık					
Kibrit					
Mouse					