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Robyn Brooke Grunberg
grun4640@mylaurier.ca

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Exploring Upper Limb Sequence Behaviours in Egocentric and Allocentric Reference Frames

by

Robyn Brooke Grunberg

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Abstract

Voluntary behaviours, such as reaching, are essential for manipulating and exploring our environment. The current body of literature, however, has predominantly investigated reach behaviours through tasks such as peg-moving, tapping, dotting, and circle drawing. The objective of this study was to investigate the order and direction of reaching behaviours in a sequential tapping task in both an egocentric and an allocentric reference frame. Gaze behaviours were observed to explore intent to reach in the sequential task. Implementing reference frames in an upper limb motor control task might be of clinical importance when exploring rehabilitation techniques post-traumatic brain injury. It was hypothesized that when one’s resting hand was in view (egocentric reference frame), the initial reach would be towards the resting hand; otherwise the long axis would be the location of the first reach (allocentric reference frame). Participants were expected to move in the clockwise direction with their right hand, and counter-clockwise direction with their left hand, similar to circle-drawing tasks. Gaze behaviours were expected to precede hand movements towards each target. Right-handed participants were asked to perform a sequential dot tapping task on a touchscreen in either an egocentric (i.e. resting hand is beside the touchscreen) or allocentric (i.e. resting hand is on their thigh) reference frame, using either their preferred or non-preferred hand. Eye movements were tracked to help identify if gaze was coupled to reaching movements. Results indicated that participants initial movement was towards the target that was closest to their midline; moving to the target near the midline might be the most efficient route towards the initial target to reduce trajectory errors and energy expenditure. Participants were equally as likely to move in the clockwise direction with the left hand as they were with the right, perhaps due to the right-hand-left-hemisphere system undergoing the decision-making process, as the right hand always performed the task first.

Similar to previous gaze research in sequential tasks, eye movements guided the hand to their initial target. A saccade was made towards the first target to be tapped, whereby gaze shifts occurred to each consecutive target in the sequence prior to tapping. These results demonstrate that in a sequence task, young adults choose the most efficient means to direct their reaches by creating an egocentric reference frame within the peripersonal space; and eye movements help in initiating where and how these movements are made. This study can be elaborated upon by future research in special populations, as well as for rehabilitation purposes in the retraining of an affected limb in post-stroke and traumatic brain injury patients.

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Key Terms

Fixation – A fixation is described as a stable attentive gaze toward a single target for a minimum of 100 ms (Land, 2006).

Reference frame – A set of axes that describes the location of an object.

Reflex – A fixed, automatic movement that occurs in response to a sensory stimulus.

Saccade – A rapid eye movement that occurs when an individual switches their gaze from one object to another (Land, 2006).

Visuomotor processing – Visuomotor processing refers to having adequate vision, as well as, the ability to control eye movements, so that cortical areas can integrate sensory information, to plan and execute necessary motor skills or tasks.

Voluntary movement – A purposeful, goal-directed movement.

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1. A Review of the Literature

The motor control literature utilizes a range of motor tasks to examine upper limb behaviours and the intention behind these movements. In a sequential reaching motor task an individual has to identify, choose, and act upon potentially multiple objects in order to fulfill a goal. Humans perform sequenced behaviours constantly throughout their day, such as when dialing in a phone number, or when making a meal. Therefore, it is important to understand how visual information from the environment informs an individual before they act. Research has shown that visual information is not always necessary to create and guide a movement (Heath et al., 2008), however, when it is available, it is important to understand how the movement is made and what each item in the sequence informs the individual. The space or the environment surrounding the individual has many cues that could affect the intentionality behind a movement. As such, this study intends to investigate how the space around an individual might influence the sequence of their upper limb movements in a visually-guided tapping task.

1.1 The Fundamentals of Manual Aiming or Reaching

The upper extremity is used for activities of daily living (ADLs) ranging from fine motor tasks, such as, grooming, eating, and getting dressed; as well as for gross motor skills such as crawling and walking (Shumway-Cook & Woollacott, 2017). Reaching is a primitive behaviour, allowing for the exploration of one’s environment and for the retrieval of desired objects (Kalaska & Rizzolatti, 2013). Unlike reflexive behaviours, these voluntary reaching movements require planning, and ultimately take longer to execute, therefore making them more complex actions (Shumway-Cook & Woollacott, 2017). Given the complexity of these fine and gross voluntary movements, there is much to understand about the coordination between the central nervous system (CNS) and the ensuing upper limb movements. Neurophysiology studies have helped illustrate the paths connecting sensory stimuli, action intentions, and subsequent motor actions. Experiments examining reaching actions have found various areas of the cortex, especially those of the parietal and frontal cortices to be active during these movements (Batista & Anderson, 2000; Andersen & Cui, 2009). Therefore, the next section will elaborate on important CNS structures involved in the planning and execution of reaching movements.

1.1.1 Neural Control of Reaching

Appropriate sensorimotor integration is an essential component of performance when reaching. Although some literature argues that movements can be made in the absence of visual information (Heath, Neely, Yakimishyn, & Binsted, 2008), other researchers suggest that spatial representations of the environment assist in the preparation of reaching movements, specifically in terms of awareness of intention (Anderson & Cui, 2009); as well as for the online control of motion (Krigolson & Heath, 2004). As such, an interplay of neuronal connections exists between sensory areas and motor areas of the cortex.

The brain is divided into left and right hemispheres. Each hemisphere supports different general skills. The left hemisphere tends to be specialized for speech production and language, whereas the right hemisphere is specialized for visuospatial awareness and attention (Flöel et al., 2005). However, both hemispheres are capable of controlling actions, specifically those on the contralateral side of the body (Haaland & Herrington, 1996). Research involving patients with unilateral damage to the left hemisphere has shown that more complex tasks such as, peg inserting, movement sequencing, and arm-hand precision tasks, seem to be greatly affected on both the contralateral and ipsilateral limbs, however; and to a much lesser degree in patients with right hemisphere damage (Haaland & Harrington, 1996; Kim et al., 1993; Haaland & Delaney, 1981). Evidently, the type of task at hand seems to influence cortical activation. Therefore, it is of importance to understand the roles of specific cortical areas in the control of upper limb movements. The current section will provide details on these functional areas responsible for movement intention, initiation, and execution.

1.1.3.1 Premotor Cortex and Supplementary Motor Area

The frontal cortex is generally known for cognitive processing and executive functioning. However, in the caudal region of the frontal lobe there are two important areas shown to contribute to the generation of movements. These areas are known as the premotor cortex (PMC) and supplementary motor area (SMA), and generally, they support sensory-guided movement and internally-guided movement (i.e. internal representations of a movement pattern) (Rizzolati & Kalaska, 2013).

The PMC works alongside the sensorimotor area of the frontal cortex in the guidance of movements (Passingham, 1988). In monkeys, neuronal activity activates when instructed to move through environmental cues but also during action (Rizzolati & Kalaska, 2013). The PMC has been further divided into dorsal (PM_d) and ventral (PM_v) areas (Rizzolati & Kalaska, 2013). Neurons in the PM_d have been shown to discharge during an action, but also during the selection of an action specific to a certain task, and in response to directionally-significant stimuli (Cisek, Crammond, & Kalaska, 2003). However, research findings suggest that neurons of the PM_d tend to be more active during sequential movements that are internally guided, as opposed to visually-guided movements (Ohbayashi, Picard, & Strick, 2016). Ohbayashi and colleagues (2016) surgically removed the PM_d from monkeys and had them perform sequential reaching tasks under two conditions: 1) visually-guided by cues, or 2) guided from memory. A marked decrease in neuronal firing only during the memory guided reaching task was found. These findings illustrate that the PM_d is more than a visuomotor interface, but it is also relevant for the reproduction of step-by-step components of a sequence. The PM_v on the other hand is more relevant for grasping, as neurons within the region fire when using precision grips and for manipulation of objects (Rizzolati & Kalaska, 2013). Specifically, the PM_v discharges during movements involving the hand and mouth (Rizzolati & Kalaska, 2013), indicating that the PM_v couples with visual information in peripersonal space or near space. Overall, the PMC appears to be necessary in the selection of appropriate actions in either externally- or internally- guided tasks.

The SMA on the other hand is important for initiation of reaching movements (Rizzolati & Kalaska, 2013), and more significantly for preparation of internally-generated movements (Ohbayashi et al., 2016; Mushiake, Inase, & Tanji, 1991). Specifically, the SMA is critical for the temporal component of sequential movements (Ohbayashi et al., 2016). In addition, the SMA prepares responses to sensory stimuli that have either been stored in memory or are self-determined (Mushiake et al., 1991). While the PMC is responsible for selecting appropriate actions from external information, the SMA is responsible for invoking proper movements, specific to the task at hand, preceding the actual physical action.

1.1.3.2 Occipital Cortex

Observations of ones' environment is one way in which humans and non-human primates gather sensory information for the production of visually-guided voluntary actions (Batista & Andersen, 2000). The occipital lobe is responsible for processing such visual information (Planelles et al., 2014). Evidence suggests that reach-related tasks involving presentation of visual targets incurs high levels of activation of the occipital lobe (Bernier & Grafton, 2010). The reason for these findings is that the occipital lobe contains the primary visual cortex (V1), linking the retina of the eye to the cortex. V1 allows for crude visual information from the environment, specifically, from the central visual field, to be rapidly integrated into the cortex, providing a sharp image of the environment. V1 works along with other extrastriate visual areas, such as V2 and V3, to process and decode aspects of visual stimuli, so that higher cortical areas can then use this information to make a movement. While V2 helps route processed visual information towards higher cortical centres, area V3 appears to be important for depth and motion processing (Arcaro & Kastner, 2015). As such, eye movements typically precede muscle activation, and thus, movement (Land & Mayhoe, 2001). This visual information supports transportation of the arm towards an object in ones’ peripersonal space, such as when ringing a doorbell; or when moving the arm back towards ones’ body, such as when eating (Fattori et al., 2005). While the occipital lobe is important for integrating visual sensory information helping to explain why certain actions are chosen for specific objects or goals, it does not explain how these movements are physically generated.

1.1.3.3 Parietal Cortex

The parietal cortex (PC) is the interface between frontal and occipital lobes, therefore it is integral for generating actions. Ultimately, the PC connects sensorimotor areas to motor planning areas, and these plans are then sent to the motor execution areas of the brain, such as the PMC and SMA. Various regions in the parietal cortex encode for reaching behaviour (Rizzolati & Kalaska, 2013). The posterior parietal cortex (PPC) has been found to be an essential area of the PC involved in performing visually-guided reaching movements (Fattori et al., 2005). The PPC contains a subdivision called the parietal reach region (PRR) which is involved in planning reach movements (Batista & Andersen, 2000). The PRR contains an area known as the lateral intraparietal area (LIP). The LIP increases activation for the initiation of eye movements or saccades (Batista & Anderson, 2000). The LIP has been proposed to guide attention as well as intention (Bisley, Mirpoor, Arcizet, & Ong, 2011). Furthermore, the LIP is active when animals are planning to make a saccade, whereby the PRR is active when animals are planning to reach (Batista & Anderson, 2000). Taken together, the role of the PPC is to integrate sensory stimuli retrieved by the LIP in order to produce congruent behaviour, which is mediated by the PRR that creates the intention for movement.

Lastly, the superior parietal cortex (SPC) of the PC is composed of neurons that encode for movements made in specific directions (Rizzolati & Kalaska, 2013). More specifically, area V6a of the SPC monitors arm-object interaction in peripersonal space, such that gaze will cause specific neuronal firing based on direction of the limb regardless of whether the object is in the field of view or not (Fattori et al., 2005). As such, neurons of the SPC would discharge and be influenced by reaches made at different orientations and angles, such as in a sequence-type task.

1.1.3.4 Primary Motor Cortex

Once the frontal and caudal parietal cortices form appropriate movement plans, actions can now be formed. The primary motor cortex (M1) is the section of the frontal cortex thought to be primarily responsible for generating motor commands for voluntary movements (Andersen & Cui, 2009). M1 gathers information from more anterior areas of the frontal lobe involved in decision-making and spatial processing (Andersen & Cui, 2009), as well as from the parietal regions, such as the PPC, PRR, and LIP (Fattori et al., 2005). When a reach is planned, M1 sends neuronal projections down towards the spinal cord so that information is further relayed to appropriate muscles, in order to induce sequential movements of the arm. Georgopolous, Schwartz, and Kettner (1986) conducted EMG recordings of rhesus monkeys as they reached from a central initial position towards different directions of targets presented on a circle in the horizontal plane. The results revealed that neuronal cells to discharge in a sinusoidal pattern and not on a one-to-one ratio, suggesting that these cells might cooperate with one another in order to generate movement in a desired direction. Studies investigating neuronal activity of M1 during visually-guided sequential tasks compared to internally-guided sequence tasks suggest that cells in M1 are equally responsive during both sets of tasks, which is contrary to what would be found in the PMC and SMA (Mushiake et al., 1991). Additionally, cells in M1 take longer to activate during pre-movement and movement execution (Mushiake et al., 1991), thereby indicating that other cortical areas are responsible for the planning of movements, while M1 is pertinent for conduction of the actual movement (Wong & Krakauer, 2019).

In summary, it is important to remember that no single area of the cortex is responsible for all the steps between intention and action (Rizzolati & Kalaska, 2013). One can see that there are many highly specialized regions influencing specific processes that proceed a reaching movement, however, connections between these areas are vital for producing actions. Visual feedback from the environment and ones' limb position in space (Heath & Binsted, 2007) has been shown to significantly contribute to successful reaching behaviours (Manzone, Loria, & Tremblay, 2018). It is important to highlight that nature of the task influences spatial awareness; and as such influences reach behaviours. Therefore, exploring vision and gaze behaviours during reaching tasks is crucial for making connections between current knowledge of sensorimotor integration and subsequent upper limb behaviour.

1.1.2 Introduction to Reaching

A motor plan is required to perform a reach. This plan is defined as "the neural process by which the location of an object in space is translated into an arm movement that brings the hand into contact with the object" (Rizzolatti &Kalaska, 2013). Behind each reach movement an internal decision is made instructing the limb whether to act or not (Rizzolatti & Kalaska, 2013). Overtime these actions become learned; with practice, movements are performed unconsciously. Therefore, tasks such as reaching for a glass of water, making a sandwich, or dialing in a phone number, all require minimal effort to complete. Animals are constantly monitoring their environment to plan and execute movements specific to a goal (Batista & Andersen, 2000). For example, Batista & Andersen (2000) recorded cortical activity of Macaque monkeys when performing a delayed-reaching task and an intervening-reach task. In both tasks the monkeys were trained to reach towards briefly presented visual targets after an 800 ms delay period. In the intervening task, the protocol was similar except a second cue was presented 600 ms after the initial cue appeared. After this first cue was presented, the monkey was given no further instructions on target location or goal for their second reach. Therefore, the monkey had to make a decision about where to reach in response to the previously displayed visual cue. Results demonstrated that neuronal discharge was specific to the monkey's choice of action. Cortical activity recordings occurred only for the planned movement and not for all the potential reaches that could have been performed. These findings suggest that goal-directed movements required first, choosing an appropriate action; second, selecting the target of action; and finally, translating sensory information of the target into proper muscular activity. However, when presented with a novel task (i.e., a task that is new to the participant) it remains unclear how intention informs movement (Wijeyaratnam, Chua, & Cressman, 2019). Some research suggests that arm biomechanics (Rosenbaum & Sauerberger, 2019; Cos, Bélanger, & Cisek, 2011), as well as context of the task (Kalaska & Rizzolatti, 2013) influence intentionality behind impending actions.

It is well established that movements are most feasible if they are within the range of motion relative to the biomechanics of a specific limb (Latash, 2010). For example, in order to successfully move an arm for reaching there needs to be sufficient range of motion and synergies between joints and muscles from the proximal-end of the segment (i.e. the shoulder joint) down towards the distal end (i.e. the wrist). By observing blacksmiths and other labourers in the 1920's, Bernstein (1967) proposed the degrees-of-freedom problem. The degrees-of-freedom problem argues that movement must be related to more than just task-relevant spatial components; but must also be possible by ways of appropriate joint and muscle activation. The degrees-of-freedom problem questioned how the CNS is capable of planning and executing movements (Latash et al., 2010); and Bernstein believed the answers were related to muscle and joint synergies, as well as environmental forces, such as external and reactive forces (Biryukova & Bril, 2012). Since Bernstein's time, research has explored the biomechanics of movements in terms of perception, learning, and neural control (Biryukova & Bril, 2012). The CNS might initiate actions by analyzing if the movement is biomechanically advantageous or convenient for the limb or body-segment, relative to the object of interest. Rosenbaum and Sauerberger (2019) performed a study investigating the effects of biomechanical influence on aiming preference during walking. Rosenbaum & Sauerberger (2019) attempted to understand the behavioural differences between picking up and placing while seated versus picking up an object while walking. Further previous research had suggested that people prefer beginning a task, such as when flipping a water glass over, in awkward hand positions in order to end the movement in a more comfortable final hand position (Potts, Brown, Solnik, & Rosenbaum, 2017). This is known as the end-state comfort effect. However, in a walking task where participants were given the choice of picking up a nearer object to move it farther or picking up a farther object to carry it less far, individuals preferred the former (Rosenbaum, Gong, & Potts, 2014). To make sense of these contradicting findings, Rosenbaum and Sauerberger (2019) conducted two experiments. They instructed participants to pick up a bucket from a stool either on their left or their right; they were asked walk to place it into a dish that either rested on a stool at waist height, or on the ground. In the second experiment the target was either at waist height or knee-level (13 inches off the ground). Ultimately, these experiments examined task completion by manipulating the height, and therefore, ease, of object placement based on limb biomechanics. As such, Rosenbaum and Sauerberger (2019) postulated that aiming would influence where participants chose to place the object, such that the waist-high target facilitate easier aiming and therefore participants would choose to place the bucket at the waist-high target level. The results of their experiments were in line with their hypotheses – participants preferred to place the objects at a height where placement height would be easiest relative to their body-segments. These outcomes are significant as they demonstrate that action intentions are at least in part related to biomechanical factors, whereby people act in accordance within the realm of their biomechanical limitations.

Further research has found similar biomechanical advantages in reaching tasks. Cos, Bélanger, and Cisek (2011) investigated how biomechanics affect movement choice when given more than one potential targets. Cos and colleagues (2011) asked participants to perform 1200-1800 reaching trials holding a stylus at an origin cue on a tablet until a “go” signal occurred. The participants then had to move the stylus towards a target region of their choice as quickly as possible. The researchers manipulated the length of the path between the origin and target position to determine if path length would affect reach behaviours based on participants’ biomechanics. To illustrate the task, Cos and colleagues (2011) modelled the arm as a two-segment rigid body rotating around shoulder and elbow joints. Cos et al. (2011) created a matrix of ellipses encompassing each of the two targets' locations for potential movements. They argued that movement along the major axis of an ellipse is biomechanically easier and will thus be preferred, as opposed to the minor axis, even though from a visual perspective the two actions appeared to be equivalent (Cos et al., 2011). The major conclusions from their study are twofold: 1) participants chose to reach towards a target along the major axis of the ellipse as opposed to the minor axis, therefore suggesting that biomechanics influence the selection of motor actions; and, 2) preferences for appropriate biomechanical trajectory are predicted by the CNS prior to the onset of movement. The outcomes from this study ultimately indicate that biomechanical properties are taken into consideration when completing a reaching task.

1.1.3 Manual Aiming

While upper limb biomechanics appear to be important in their contribution to reaching movements (Cos et al., 2011), there is also evidence to suggest that decision making for motor actions might be influenced by other factors, such as risk-minimization (Trommershäuser, Maloney, & Landy, 2008) and perceptual visuomotor processing (Batista & Anderson, 2000). Much of this literature argues that uncertainty plays an essential role in manual aiming. These studies suggest that visual perceptual cues, such as depth and background motion, ultimately influence cognition, and therefore, the perceptual control of movement (Landy, Maloney, Johnston, & Young, 1994). People tend to use such perceptual cues to their benefit to minimize movement failure and maximize gain (Trommershaüser, Maloney, & Landy, 2008). For example, Proteau and Masson (1997) examined goal-directed manual aiming in a perturbation paradigm. Participants were instructed to move a cursor towards a target on a screen. During certain trials the visual background would move in either the same direction, or the opposite direction of the cursor controlled by the participant. Findings from the study indicated that aiming movements were longer and undershot in the perturbation trials. Therefore, perturbation of a visual background will elicit slower and less accurate aiming responses. These results are significant because they explain that background information might modulate the speed at which the hand approaches an initial target, and therefore determines whether or not an action will be successful or not. Furthermore, these results suggest that participants' aiming responses are impacted by spatial representations relative to the object of interest (i.e. an allocentric reference frame) (Proteau & Masson, 1997). To note, spatial reference frames will be discussed later in Chapter 1. In another experiment by Roy, Kalbfleisch, and Elliott (1994), participants were instructed to use a stylus to point at a target presented on either their left or right as quickly as possible in either vision or no-vision conditions. This study aimed to identify differences in efficiency of visual processing between the hands to successfully point towards a goal. The right hand was found to be more effective at eliciting quicker and more accurate aiming responses. These results are in-line with neurophysiology research which suggests that the left-hemisphere, right-hand motor control system is generally more efficient than the right-hemisphere for visual processing for action (Haaland & Harrington, 1996). Findings from their study highlight another factor that might contribute to efficient visual processing for manual aiming, namely, handedness. As such, handedness will be discussed further in section 1.4. Although in this project there were no visual perturbations or removal of visual feedback, it is important to highlight the integrity of manual aiming responses when visual feedback is removed and when altering the visual background in order to understand the role of uncertainty of condition and vision during aiming behaviours.

With the above experimental findings, the literature examining the relationship between motor planning and manual aiming remains inconclusive. Many factors appear to contribute to manual aiming behaviours. The speed at which the CNS is able to process visual information can affect motor output between hands. Therefore, the next section will examine the importance of investigating vision during upper limb tasks.

1.2 Evaluating Gaze During Reaching Tasks

Evidence suggests that animals respond to visual stimuli by observing the space and objects present in their environment (Hayhoe, 2000). This literature found that humans seek out relevant information and cues from their surroundings in order to guide their actions. Research has also shown that observers are not as sensitive to changes in visual scene as one may think (Simons & Levin, 1977). In the previous section, the different cortical areas responsible for either integrating visual stimuli, for subsequent translations into motor plans, or for the execution of actions, were discussed. When analyzing gaze behaviours, eye movements usually precede their intended motor actions by a fraction of a second (Land & Hayhoe, 2001) and eye movements depend on the context of the task (Kalaska & Rizzolatti, 2013). Therefore, gaining a deeper understanding of gaze behaviours preceding and during voluntary movements is essential for investigating connections between motor planning, intention, and execution of a motor action specific to a task.

1.2.1 The Two Visual Stream Hypothesis

In order to identify how visual processing varies depending on the task, the two visual stream hypothesis will be discussed. Early work by Goodale and Milner (1992) speculated that during visually-guided reaching two distinct visual pathways exist: one that uses vision to mediate perception tasks, and the other processing vision to mediate actions. According to the two visual stream hypothesis, visual projections either inform behaviour based on perceptual or action-mediating visual cues. When required to process visual information of colour, size, shape, or orientation, a vision-for-perception stream is utilized. This visual pathway is known as the ventral visual stream and the visual information gets processed by V1 and other visual cortex areas using conscious visual control. The information projects further to the inferior temporal lobe, an area involved in pattern discrimination and recognition (Beke, Findall, & Gonzalez, 2018; Goodale & Milner, 1992). On the other hand, when vision is processed to inform motor action, projections are received by the PPC of the PC in an online manner, which means that vision is being processed simultaneously to movement in order to correct for potential errors. This pathway is known as the dorsal visual stream (Beke et al., 2018). The functional aspects of the pathways were established during the initial investigation of patient D.F., a woman suffering from bilateral damage of her occipitotemporal cortex and thus, her ventral stream. In multiple studies D.F. was incapable of judging and demonstrating how she would perform a perceptual reaching tasks, such as orienting a piece of mail into a mail slot, although, she was perfectly capable of performing reaching actions (Ganel & Goodale, 2019; Goodale & Milner, 1992). Having basic knowledge of the two visual streams is essential for our project. Therefore, action-oriented sequential reaching tasks, the dorsal stream would be predicted to be mediating visual processing, and as such, gaze behaviours might be expected to be shorter in length (Hayhoe, 2000), especially in comparison to ventrally-mediated actions performed from memory.

Further investigations of the ventral and dorsal visual pathways have observed human reaching behaviours during vision and no-vision conditions (Heath, Neely, Yakimishyn, & Binsted, 2008; Binsted et al., 2007; Heath & Binsted, 2007; Krigolson & Heath, 2004). These studies were useful in identifying how neurotypical individuals process visual stimuli in what would be considered a ventral stream (i.e. without vision) versus dorsal stream (i.e. with vision) reaching task. While some of the literature has found that in neurotypical individuals two distinct visual streams exist for the mediation of perceptual versus action-related visual information (Beke et al., 2018; Ludwig, Sterzer, Kathmann, & Hesselmann, 2016), others have countered this notion. For example, Heath et al. (2008) examined goal-directed reaching behaviours after 0 (D0), 1000 (D1000), and 2000 (D2000) ms of visual delay. In the D0 condition, participants were required to point towards a cued target circle within an array of circles at the same time as an auditory cue (i.e. the cue to initiate movement) was presented. In the D1000 and D2000 conditions, the initiation tone was presented at either 1000 or 2000 ms after the array of circles were presented and removed. Therefore, participants had to remember the size and location of the target circle. It is known that the ventral visual stream has a very short-term memory of the visual world (Ludwig, Sterzer, Kathmann, & Hesselmann, 2016). Once vision is no longer accessible to an individual, the accuracy of the ventral visual stream becomes much less accurate as visual stimuli can only be stored within this area for brief periods of time. However, results indicated that target size information (i.e. perceptually-mediated stimuli) were available to elicit motor output even after the longest delay condition, thereby implying that visual information for movements are not necessarily only available when controlling movements online, or moment-by-moment. Research has gone further to suggest that other factors may in fact be responsible for the observed differences between ventral and dorsal streams. These studies argue that spatial representations of the environment may impact reaching behaviours, rather than the type of task (i.e. a perception versus action task) (Schenk, 2006; Khan, 2005; Krigolson & Heath, 2004). Moreover, the relevancy of environmental features during such a task appear to be better understood while simultaneously observing gaze behaviours (Young, Withrow, & Sarkar, 2017).

As such, it would be of interest to examine and manipulate individual's spatial representations of targets and their limb in a reaching task.

1.2.2 Gaze Behaviour and Eye Tracking During Goal-Directed Movement

Vision is important for the regulation of goal-directed upper limb movements (Elliot, Carson, Goodman, & Chua, 1991). In order to understand more about visual information processed by V1 and the ventral and dorsal streams, it is crucial to understand that there are different types of eye movements made during a given task. When scanning an environment for pertinent stimuli, faster eye movements are necessary to bring the eye towards a target of interest (Hayhoe, 2000). However, when a task requires more attention, gaze might be locked onto a target for a longer period of time in order to gain more visual information about the object (McFarland et al., 2015).

1.2.2.1 Fixations and Saccades

Eye movements are understood in terms of fixations and saccades. Fixations are moments where the eyes are relatively stable, indicating currently relevant information for task performance (Ballard et al., 1995). On the other hand, saccades move the eyes from one visual target to the next and occur between 20-35 milliseconds (El Haddioudi & Khaldi, 2012). However, other literature identifies that saccades can last shorter than 20 milliseconds or longer than 35 milliseconds, extending to about half a second (Land, 2006). Humans have been found to make several saccades per second, as such scanning their environment for interesting information in the environment (Brouwer, Medendorp, & Smeets, 2016). Eye tracking is often used to measure gaze behaviour toward a stimulus as it objectively measures focus of attention (El Haddioui & Khaldi, 2012). The current body of literature reports that during natural tasks, such as preparing to make a cup of tea, or when making a peanut butter sandwich, the eyes tend to fixate upon objects as long as that object is being acted upon (Land & Hayhoe, 2001). Conversely, saccades are made quickly, scanning the environment, looking for the next relevant target necessary for completion of an upper extremity task (Land & Hayhoe, 2001).

1.2.2.2 Gaze Provides Insight into Intention

Eye-tracking gaze behaviours are important when investigating interactions between the environment and decision-making (Ballard, Hayhoe, Li, & Whitehead, 1992). As discussed, intention may be related to actions that are permissible to the individual based on limb biomechanics and range of motion about a joint (Cos et al., 2011). In such a case, measuring gaze behaviour would establish whether individuals look at their limb, the target, or objects within their visual field in order to determine what actions they are capable of producing. Experimental studies measuring gaze behaviours in visually-guided pattern response tasks have found eye fixations to inform the decision-making process during hand movements. Ballard & colleagues (1992) created a hand-eye coordination block-copying task in which participants had to copy a model into a work area on a computer screen, dragging blocks through use of a cursor. Participants were free to use any eye or hand movements of their choice. Eye-tracking was measured to assess eye movements preceding, during, and after conducting the task. In order to accomplish the task, participants were required to perform discrete movements in order to accomplish the overall goal. The findings indicated that a variety of eye movements were made throughout the completion of the sequential copying task. Participants demonstrated minimal memorization strategies; instead, participants showed a pattern whereby they would fixate to the block they wanted to remember; a second fixation would then move the eyes towards the block they were going to pick-up, and finally, they would move and drag the chosen block into their workspace area. Although participants made eye movements just prior to making hand movements, they also performed multiple saccades earlier in the task in order to gather information that would aid their block-choice and ultimately, movement decisions. Therefore, such gaze behaviours are critical for generating movement plans preceding each discrete step in the sequence process. Using a similar paradigm, Ballard and colleagues (1995) determined that eye movements are serialized to gather information just prior to being required for movement. Attention towards a specific target is limited by eye movements towards the next relevant cue for the intended movement (Ballard et al., 1995). As such, the visuomotor system is intricately and actively connected to the surroundings.

While the visual system is constantly tracking the environment for potential objects to act upon, the eyes have been shown never to fixate on the hand (Gesierich, Bruzzo, Ottoboni, & Finos, 2008. Rather, gaze research has shown an anticipatory nature of the eyes relative to the planned movement (Gesierich et al., 2008; Land & Furneaux, 1997). The eyes fixate on objects of interest in order to provide accurate visual feedback of hand position, ensuring successful guidance of the hand towards a target. Furthermore, when the hand is not directly in the field of view, such as during a game of table tennis or when typing, actions can still be produced based on target location (Land, 2006). Therefore, the tendency to direct gaze towards a goal suggests that individuals gear their vision towards objects needed to be acted upon, providing the CNS with relevant egocentric information about the location of the object relative to the body. Bowman and colleagues (2010) investigated gaze shifts during a sequential reach and tap task. In the study, participants moved a robotic-handle device towards a sequence of targets. Participants were instructed to reach and lightly touch targets from left to right before returning to the initial position. Visual feedback of the handle was provided in one block of 70 trials (i.e. visual and tactile feedback provided); however, visual feedback was removed in the next block of 70 trials (i.e. participants experienced tactile feedback only – the tactile feedback was a reactive force generated upon the participants' hand during target contact). Findings were similar to those of Ballard et al. (1992, 1995), whereby fixations were made towards each discrete target. Although, in Bowman and colleagues (2010) experiment, participants fixated on each individual target until after the handle made contact with the target, rather than fixating on the next step in the task (Ballard et al., 1992, 1995). These results are of interest as they suggest that although both tasks were sequence ordering tasks composed of discrete targets, different salient information, as indicated by a gaze shift, were necessitated in the planning of a movement.

1.2.2.3 Where do People Look During Natural Tasks

Although the aforementioned gaze experiments allowed participants to freely choose their eye and hand movements; for our study, it is important to understand where individuals direct their eye movements during natural situations. For example, Hayhoe (2000) examined participants' gaze behaviours while making peanut butter and jelly sandwiches. Results from the study indicated that all participants performed similar fixation-reach behaviours despite being given unspecific instructions. Participants in this task fixated from object to object based on what they needed next for their sandwich preparation. These results are similar to other findings (Bowman et al., 2010; Ballard et al., 1992, 1995), suggesting that humans prefer to acquire task-relevant visual information just when it is needed, rather than storing it in memory. Therefore, direction of gaze specifies the location of required information in the visual scene and the time when it is required. Hayhoe's (2000) experiment illustrated the importance of examining gaze during visual routines. Visual routines describe perceptual spatial relationships; ones that might be affected by task and intention (Hayhoe, 2000). Hayhoe (2000) explains that basic cognitive processes, such as decision-making, takes tens of seconds. However, performing sensorimotor tasks, such as dialing a phone number, require several seconds in order to associate working memory with several fixations over different positions. While the temporal aspects of visual integration have been well-investigated (Saber, Pestilli, & Curtis, 2015; Bowman et al., 2010) more research needs to be conducted to examine how spatial variables between target and upper limb influence visual routine comparing between tasks, and more specifically, in sequential-type tasks. Consequently, this project intended to investigate spatial mode or reference frames as pertinent to gaze behaviour, and therefore, reaching behaviour.

1.3 Egocentric and Allocentric Reference Frames

Evidence suggests that spatial awareness and spatial modes influence reaching behaviour by creating meaningful movements that rely upon spatial representations of the world in either world-centred, or body-centred coordinates (Wiestler, Waters-Metenier, & Diedrichsen, 2014; Lemay, Bertram, & Stelmach, 2004). However, the majority of these investigations have been performed in visuospatial learning or memory tasks. There are currently limited investigations that have manipulated reference frames during a skill, such as a sequencing reaching tasks, while simultaneously measuring gaze behaviour.

1.3.1 Spatial Representations

As discussed in earlier sections, eye movements are made towards relevant visual cues. V1 and other visual cortical areas then process the visual information. Whether visual projections are prompting a perceptual-mediated response or a motor action-mediated response, the cortex needs to have adequate knowledge of the surrounding space; as well as where the limb is positioned relative to other body parts and objects in the space, in order to perceive an action or to physically move. Spatial representations explain the way in which the world is represented in the cortex (Klatzky, 1998). The binding problem is a phenomenon that suggests that the visual system is capable of processing features of objects within the environment (Isbister et al., 2018). These object features will guide actions when vision is present. As such, the vision-for-perception and vision-for-action stream has been questioned as more recent research has suggested that patient D.F.'s ventral stream impairments might actually correspond to object-oriented spatial representations, as opposed to perceptual tasks (Schenk, 2006).

In reaching actions, the arm typically moves from an inward position, starting the task closer to the body, followed by moving to an outwards position, closer towards the target. The space that surrounds an individual is known as the peripersonal space (Fattori et al., 2005). Egocentric reference frames represent an object's location in peripersonal space relative to one's body (Neely et al., 2008; Lemay et al., 2004). For example, when reaching outwards as to reach for a glass of water, a comparison is being made from the body to the glass. On the contrary, an allocentric reference frame represents peripersonal space relative to external objects, independent from an individual's position (Neely et al., 2008; Lemay et al., 2004). For example, when reaching to unlock a door, the allocentric reference frame is defined as where the key hole is in comparison to the lock itself.

When Schenk (2006) re-examined D.F. and compared her perceptual and action (via reaching) behaviours compared to ten age-matched women, Schenk (2006) found that her perceptual behaviours were significantly impaired. However, Schenk (2006) dissociated the behavioural task and spatial mode in his paradigm, D.F. and the other participants performed a perceptual and visuomotor task using either allocentric or egocentric information. In the perceptual, allocentric task, participants had to judge and state which of two dots were closer to a cross. In the perceptual, egocentric task, participants had to rely on proprioceptive information based on the tip of the finger to determine which dot was closer to the cross. During the motor task, the allocentric condition required participants to point to a target with a position relative to the cross (i.e. an external reference point). During the egocentric condition, participants had to move their finger from an initial position to the target position. Schenk (2006) found that D.F. was perfectly capable of performing in both perceptual and visuomotor egocentric conditions, however, her behaviour was significantly impaired in both perceptual and visuomotor allocentric conditions. Therefore, contrary to the perception-action model, D.F. is capable of producing perceptual-mediated tasks, however, she is incapable of performing in allocentric reference frames.

The findings of the aforementioned study by Schenk (2006) are important for this project as they identify that spatial representations are essential to movement and might impact both action and perceptual behaviours. As a result, manipulating reference frames during a task can relay crucial information about visuomotor processing and intention behind movements. In our project, reference frames might be useful in identifying why an initial pointing movement is made. Since an egocentric reference frame is related to where the limb is with regards to the body, and vision anchors with the most relevant target, these connections might warrant beginning the task at a point that is visually closest to the hand. The benefits of investigating reference frames and gaze behaviours in a manual aiming task therefore allow researchers to make sense of intentions in the CNS and the visual world.

1.3.2. Goal-Oriented Reaches Rely Upon Reference Frames for Different Tasks

While Schenk's (2006) research is compelling, more research investigating the influence of reference frames in healthy individuals is necessary in order to increase understanding of how spatial representations affect intention and behaviour. There is limited evidence that has explored how reference frames can affect behaviour in a motor sequential task. Some literature using visuomotor delay tasks has alluded to the fact that the perception-action model does not explain why visual information could be acted upon after 2000 ms of delay (Heath et al., 2008; Binsted et al., 2007). The authors suggested that their findings might be better explained by examining ego- and allocentric reference frames (Heath et al., 2008; Binsted et al., 2007). Another example by Neely et al., (2008) argued that when visual information is available during a goal-oriented reaching task, egocentric visual cues primarily attend to the online control of movements. However, when visual information is unavailable, allocentric visual cues are more favourable for reaching.

When examining movement accuracy, Lemay et al. (2004) determined that pointing towards a remembered target in an allocentric frame of reference is more stable than pointing to a remembered target in an egocentric reference frame. Specifically, participants were asked to point to a target in either: 1. A completely dark environment (egocentric coding); 2. A condition in which the target was in an illuminated square (egocentric or allocentric coding); or 3. A moving condition in which the target shifted to a different location when having to be recalled (allocentric coding). It was found that pointing to a remembered target in an egocentric condition was more variable than when pointing to an allocentric condition as egocentric information might decay over time, whereas allocentric information might be more stable (Lemay et al., 2004). These results suggest that during reaching, reference frames can also be indicative of decay in visuomotor memory, and thus, accuracy.

Finally, an experiment investigating visuomotor learning whilst using a discrete sequencing task examined the influence of reference frames on sequencing of reach behaviours (Kleine & Verwey, 2009). When researchers manipulated the position of the hand to change the spatial representation used by participants during the task, results illustrated that execution of the learned sequence was performed based on spatial coordinates. However, spatial coordinates did not influence the transition phase from when a task was pre-learnt to when the skill became learned.

These studies either found that reference frames influence reach behaviours during different tasks (Neely et al., 2008; Lemay et al., 2004); or they manipulated hand position as to investigate whether reference frame influenced motor learning or not (Kleine & Verwey, 2009). In the completed project participants’ hand position will be changed to examine the effect of reference frame on initial movement. In order to understand the influence of hand position, and potentially reference frame, on reach behaviours, it is necessary to explore handedness in the performance of specific tasks; and most importantly for our research, sequence-type tasks.

1.4 Evaluating Handedness and Reaching Behaviours

Handedness is defined as a preference towards using the right or left hand (Raw et al., 2012). Cerebral lateralization is generally considered to be responsible for controlling the contralateral limb, such that the performance of left-handed individuals would be thought to primarily be controlled by the right hemisphere, whereas the performance of right-handed individuals would be controlled by the left-hemisphere. However, this is not necessarily the case (Chapelain et al., 2012). Hand preference has been shown to be affected by a number of intrinsic factors, such as, sex and age, as well as extrinsic factors, such as, task (Chapelain et al., 2012). People typically use their preferred hand for complex skills such as writing or playing an instrument, and their non-preferred hand for less difficult skills such as picking up a glass (Bryden & Roy, 1999). The current body of literature has examined handedness and reaching behaviours across a variety of tasks.

1.4.1 Peg-moving

Early research investigating handedness tested participants’ skill using a pegboard developed by Annett (1972, 1976) (McManus, Van Horn, & Bryden, 2016). In peg-moving experiments, participants’ handedness would be measured by examining performance of each hand (Roy, Bryden, & Cavill, 2003). For example, Annett & Kilshaw (1983) examined age and sex using a pegboard task. Results showed that speed of task completion increased up until 50 years old, whereby afterwards speed decreased slightly. Males were typically faster than females in all age groups when using the left hand, whereas females were faster with the right hand until 10 years of age (Roy, Bryden, & Cavill, 2003). Moreover, Roy and colleagues (2003) found similar results whereby participants show right-hand advantages and differences in hand performance exist as a function of age. Although findings from peg-moving tasks are important for upper limb research, they are relatively inefficient and difficult to administer to a group of participants (McManus et al., 2016).

1.4.2 Tapping and Dotting

Finger tapping tasks have also been crucial for exploring handedness across a variety of age groups. Tapping tasks are made up of discrete reaching movements. When performing a series of discrete movements, a number of sub-movements are made to reduce error made by previous sub-movements; and these rely more on cognitive processing to ensure for successful aiming; typically, this is related to reducing end-point error (i.e., variability) (Elliot et al., 1991). Fitts’ (1954) proposed that the index of difficulty during a tapping task could be represented by bits of uncertainty (Salmoni & McIlwain, 1979). Tapping tasks require precise finger movements. The degree of uncertainty is larger with narrower targets and with greater amplitudes, as number of movement choices will increase, thereby increasing complexity of the task (Salmoni & McIlwain, 1979). Similar to performance in peg-moving tasks, differences between the hands seems to be relatively stable throughout different age groups (individuals aged 7-22 years old) (Ruff & Parker, 1993).

Moreover, the Tapley-Bryden (1985) dot-marking tasks require participants to mark a dot in a circle as quickly as possible (McManus et al., 2016). Contrarily to many peg-moving and tapping tasks, dot-marking tasks demonstrated significant age-related differences in performance between children, adolescents, younger adults, and older adults; however, not between the young adults and older adults (Gooderham & Bryden, 2013).

1.4.3 The QHP Task

The Bishop (1996) Quantification of Hand Preference (QHP) Task measures reaching behaviours using spatial constraints. It is interesting in that it has shown that position of an object significantly influences hand use (Chapelain et al., 2012). In monkeys and humans, the QHP task demonstrates that reaching actions are spatially-dependent, such that the hand closest to the object will be used for the task (Musalek, Scharoun, & Bryden, 2016). In fact, Chapelain et al. (2012) found that hand lateralization may be abandoned in cases where an object is closer to a certain position in the hemifield, such that a closer object in the left will be acted upon by the left hand, even if the subject was right-handed. The QHP task illustrates that laterality is influenced by intrinsic and extrinsic factors.

1.4.4 Circle-drawing

Circle-drawing applies the degrees of freedom phenomenon, as movements should be comfortably made about joints of the arm when completing the task (Ryu & Buchanan, 2004). The shoulder and elbow joints are required for successful arm movement. Circle-drawing movements are continuous in nature and demonstrate directionality, such that the right hand has been shown to lead drawing in the clockwise direction, whereas the left-hand demonstrated leading drawing in the counter-clockwise direction (Franz, Rowse, & Ballantine, 2002). These results make sense from both a handedness and biomechanical perspective, such that moving from a point further away from the body and back towards ones' body while using the most dominant hand would be most comfortable and accessible. These multi-joint tasks more closely resemble ADLs, and therefore are imperative to observe experimentally (Krabben et al., 2011). Additionally, circle-drawing experiments have been used to compare post-stroke patients with healthy controls to examine neural recovery and/or neural plasticity post-stroke (Krabben et al., 2011).

These early reaching tasks are still used to investigate reach behaviours. However, many other tasks have arose from these initial experiments to explore upper limb behaviours between different age groups, sex, and hands. The overall conclusion from the literature examining reaching behaviours and handedness suggest task-specific behavioural components. In certain tasks, direction (Franz et al., 2002) and spatial representations (Chapelain et al., 2012) evidently impact reach behaviours. While the aforementioned tasks have been conducted in a range of populations (Mcmanus et al., 2016; Raw et al., 2015; Chapelain et al., 2012; Raw et al., 2012), it is necessary to continue to test handedness and reaching behaviours in novel tasks because of the task-specificity of reaching behaviours. Specifically, it would be of importance to experiment with sequential type movements that are similar to tasks of daily living (Kalaska & Rizzolatti, 2013). Moreover, some of the current experimental devices are not portable or easy-to-use by special populations. Therefore, a simply designed and transportable novel task would be beneficial for conducting research in healthy populations for preliminary results; and in the future, for a variety of special populations.

1.5 Rationale, Objectives, and Hypotheses

1.5.1 Rationale

It is evident there are gaps in the literature examining reach behaviours in sequential tasks, especially when manipulating for reference frame. Furthermore, it is unknown how gaze might influence each individual reaching movement, as well as overall completion of the task. Although extensive research has examined upper limb responses during peg-moving, tapping, dotting, and circle-drawing tasks (McManus et al., 2015), it is unknown how individuals order their reach behaviours when presented with a series of discrete targets that are part of a sequential task. An important component of behaviour is the intent behind action (Kalaska & Rizzolatti, 2013), and gaze location may provide crucial information about an individual's movement intention (Hayhoe, 2000). Therefore, gaze tracking added another dimension to the understanding of where and why participants might begin the sequence task at a certain target.

According to early literature on patient D.F., providing the framework for the two streams of visual processing hypothesis (Goodale & Milner, 1992), the dorsal visual stream processes vision for action, whereas the ventral stream processes vision for perception (Beke et al., 2018). D.F.'s incapacity of pursuing a perceptual task due to an impaired ventral stream might better be explained as an allocentric-processing deficit (Schenk, 2006). When performing a reaching task within ones' peripersonal space, however, an individual might rely upon egocentric reference cues for movement (Forsyth, Puckering, & Bryden, 2015). Therefore, spatial frames of reference were manipulated in this novel reaching task in order to extend upon early and current knowledge on reaching and tapping behaviours. As has already been noted, spatial reference frames seem to be guided by different reference frames, as D.F. experienced atypical behaviours when reference frames were manipulated. As such, it is possible that reference frames play a greater role in the guidance of behaviours, and might be associated with different neuromotor pathways after an injury. The findings from this study might have implications for clinical populations, such as those who have experienced a form of traumatic brain injury or stroke. The idea relates to neuroplasticity and interhemispheric transfer of information from one hemisphere to the other (Sterr, Freivogel, & Voss, 2002).

1.5.2 Objectives, Hypotheses, and Dependent Variables

Primary Objective, Hypotheses, and Dependent Variables

The primary objective of the current study was to investigate the reaching sequence order of young adults when performing a sequential tapping task that is composed of individual discrete targets in an egocentric and an allocentric reference frame. Specifically, the study was conducted to identify where participants initial tap occurred and in which direction participants completed the task. As discussed previously, peg-moving, tapping or dotting, and circle-drawing are all effective tools for measuring handedness. However, there are other ways in which these tasks can benefit upper limb movement behaviour literature. Research suggests that gaze couples and precedes upper limb movement behaviours (Helson, Elliot, Starkes, & Ricker, 2000) as to provide insight into the connections between intentions created by the CNS (areas such as the PMC and SMA) and movement execution (mediated by M1). The current task was similar to a dotting task as it involves manually aiming, or pointing, to discrete targets presented in a circle. It was also similar to a circle-drawing task as more than one target was presented, fashioned in a circle-like shape. In addition, reference frames may have adjusted behavioural responses. As Schenk (2006) argued, vision-for-perception and vision-for-action research might benefit from observing tasks done in egocentric and allocentric reference frames because spatial modes might influence behaviour under the two-visual streams hypothesis. Therefore, the novel sequence task in the current study might contribute to current knowledge on sequencing behaviour within egocentric and allocentric conditions; as well as during conditions of using either the preferred- versus non-preferred hand. Further, it might have beneficial purposes for clinical populations.

In-line with the primary objective of our study, the following manual aiming behaviours were hypothesized:

1) The direction of sequence completion will be influenced by the hand performing the task. When performing the task with the right (preferred) hand, participants were expected to move in a clockwise (CW) direction. When performing with the left (non-preferred) hand, it was believed that participants would complete the task in a counter-clockwise (CCW) direction. As mentioned in section 1.4.4., the sequence task is most similar to tapping and circle-drawing. Bimanual circle-drawing research examining handedness and the direction of movements suggests that the right-hand prefers completing the task in the clockwise direction, whereas the left hand will draw in the counter-clockwise direction (Franz, Rowse, & Ballantine, 2002). In circle-drawing tasks examining handedness, it has been found that the hand in use directs sequence completion. These findings support the idea that the right-hand will prefer performing in a CW direction, and CCW with the left-hand (Scheirs, 1990).
2) Frame of reference will influence where participants begin the sequence task. It was believed that in the allocentric condition, participants would be influenced by the long axis of the circle or ellipse and begin the task at the furthest point from their body (Neely et al., 2008; Lemay et al., 2004). However, in the egocentric condition, participants were expected to begin the task at the point that is closest to their resting hand due to a reference frame formed between the resting hand and the target closest to the hand (Neely

et al., 2008). Research suggests that in manual aiming tasks when the hand is not visible, objects in the environment (i.e. allocentric frame of reference) influence initiation of manual aiming (Proteau & Masson, 1997); but when the hand is visible, movements are influenced by direct visual-feedback about the hand's position in space (Velay & Beaubaton, 1986). The position of the resting hand was manipulated during the task to determine the effects of an egocentric reference frame versus an allocentric reference frame.

Secondary Objective, Hypotheses, and Dependent Variables

The second objective of the study was to examine gaze behaviours during the tapping sequence task to identify participants' gaze behaviours before and during reaches. It was hypothesized that in all conditions gaze movements would precede hand movements (Hayhoe, 2000; Land & Hayhoe, 1999) and that reach order would follow the same direction as gaze (Hayhoe, 2000; Land & Hayhoe, 1999).

In natural sequence tasks, gaze duration on an initial target typically greater than 100ms, therefore suggesting that a fixation has been made (Land, 2006). Therefore, it was believed participants would fixate upon the first before reaching towards this target. The literature suggests that throughout natural sequence tasks, other targets cause gaze to shift and this lasts about 70 ms (Hayhoe, 2000). It was thus hypothesized that participants would shift their gaze towards each target in the sequence before tapping; and this gaze shift would last for approximately 70 ms.

2. Methodology

2.1 Participants

Twenty-six right-handed individuals between the ages of 18-30 years of age (n=16 females) were recruited to participate in the study. Each participant provided their written informed consent upon arrival to the laboratory. Participants were not be included if they: 1) self-reported any musculoskeletal; or neurological disorders or deficits limiting their ability to use their arms to point to a target; 2) self-reported a visual impairment that could not be corrected to a minimum of 20/70; or 3) reported being left-handed or ambidextrous as demonstrated on the Waterloo Handedness Questionnaire. The study protocol was approved by Wilfrid Laurier University's Research Ethics Board.

2.2 Protocol

Participants were asked to read and sign consent forms upon arrival to the Lifespan PsychoMotor Behaviour Lab (NC104) in Northdale Science Research Centre at Wilfrid Laurier University. Participants also completed the Waterloo Handedness Questionnaire to determine the degree of right-hand dominance. The participants were then seated at a table in front of a Dell (#ST2220T, 21.5 inch) touchscreen computer monitor which displayed the targets arranged in a circular or elliptical orientation to be tapped (refer to Fig. 2.1). Oral instructions were provided to the participants by the primary researcher. Participants were asked to reach out, tap and extinguish a series of circles (the targets) presented on the touchscreen with their Index finger (2nd digit), one at a time, in sequence, without any specific instructions as to where they could or should begin. Participants were explicitly asked to: "extinguish the series of circles presented on the screen with your Index finger beginning at any target you'd like, and in whichever direction you prefer. You must complete the sequence in a consecutive order.” Once a circle was touched, it was extinguished; and the next trial commenced once all the targets were extinguished. Each of the participants results were recorded on the touchscreen through the Unity program running the experiment, such that the initial tap location, as well as the direction of their sequence was recorded. The targets were presented in randomized blocks of a potential five orientations on the screen. The targets were oriented in the shape of either a circle or four differently oriented ellipses. The five potential orientations of the targets were as follows (see Figure 2.1): 1) circle; 2) vertically-oriented ellipse; 3) horizontally-oriented ellipse; 4) ellipse stretched out diagonally to the upper right quadrant (i.e. rightwards); or 5) ellipse stretched out diagonally to the upper left quadrant (i.e. leftwards). The circle was used as a catch-trial in the experiment and participants’ performance on this shape were not analyze. However, the participants’ performance on the four different ellipses were analyzed for purpose of understanding whether the differently orientated targets influenced subsequent behaviours. Participants underwent trials in both egocentric and allocentric reference frames. In the egocentric reference frame, participants placed their resting hand in an “L” shape beside the computer screen ipsilateral to the resting hand. In the allocentric reference frame, participants placed their resting hand on their lap. In Lemay et al., (2004), conditions of egocentricity were based on proprioception, as the egocentric condition occurred in a dark environment so vision was unavailable to help guide movements. In this study, similar to Schenk (2006), participants completed the motor task with the hand in their visual field of view to provide an egocentric reference. A cross was presented in the middle of the screen to provide an external point of focus that was consistent across all trials and conditions.

Gaze data was collected on the Tobii Pro Eye Tracking device and uploaded to the laboratory’s computer, where the primary research had access to analyze the data.

Prior to the start of the experimental trials, each participant performed one block of four practice trials, to familiarize themselves with the experiment. The practice trials allowed participants to practice the tapping task with each hand and using both reference frames; the orientation of targets was randomized. Each participant then performed 12 blocks of randomized experimental trials. Each block of trials consisted of five trials (i.e., one trial for each target arrangement). In each block participants began using their preferred (P) hand, followed by their non-preferred (NP) hand. Right hand preference was confirmed using the Waterloo Handedness Questionnaire (i.e., overall score >0). However, the condition of egocentric (*ego*; see Figure 2.2) versus allocentric (*allo*; see Figure 2.3) reference frame was counter-balanced across participants. For example, Participant 1 began Block 1 using their P hand and the *ego* condition, then performed Block 2 with their NP hand and the *ego* condition, Block 3 and Block 4 followed the same hand order during the *allo* condition. Therefore, Participant 1 performed the task in the following block order: 1) P, ego; 2) NP, ego; 3) P, allo; and 4) NP, allo. Participant 2 also began the task using their P hand, however, they began the task in the *allo* reference frame. As such, Participant 2 performed the task in the following block order: 1) P, allo; 2) NP, allo; 3) P, ego; and 4) NP, ego. The block order was repeated a total of three times per participant. Thus, a total of 60 trials (i.e., 4 blocks of 5 trials each x 3 repetitions) were performed per session. Participants were informed that they could take a break at any time.

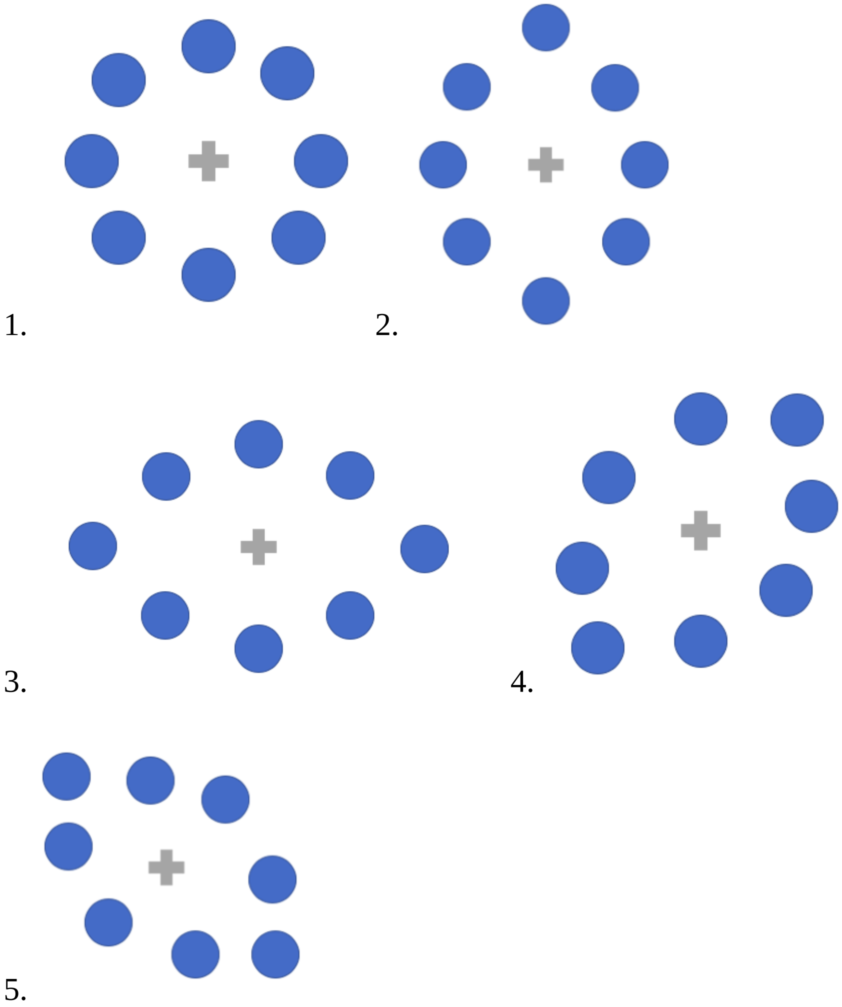


Figure 2.1 - Orientations of the targets presented on the touchscreen. 1. The circle orientation that was used as a catch trial. 2. The vertical orientation of the targets. 3. The horizontal orientation of the targets. 4. The leftward orientation of the targets. 5. The rightward diagonal orientation of the targets.

2.3 Experimental Design

The experiment was conducted at a 76cm high desk facing a blank wall of the laboratory. The desk supported the touchscreen computer screen, which measured participants' actions: 1) where they began the task; and 2) the direction that they completed the sequence. Participants were outfitted with Tobii Pro Eye tracking glasses to measure their gaze behaviours throughout the experiment at a sampling frequency of 100 Hz. Gaze location was defined by participants' gaze at a stable location (i.e., < 1 degree) for a minimum of 30 ms (i.e., 3 frames), whereas a fixation was defined as maintaining a stable gaze for more than 100 ms (i.e., 10 frames) as this is the minimum amount of time it takes for the nervous system to process visual information (Bullier, 2001).

Fig. 2.2 – Experimental set up A) Egocentric reference frame B) Allocentric reference frame.

2.4 Data and Statistical Analyses

Initial Tap

The first dependent variable related to reaching behaviours was percentage of trials that began at each of the eight targets. To measure the percentage of total trials beginning at each target, the independent variables were: 1) target orientation (1-8); 2) hand (P vs. NP); and 3) reference frame (ego. vs. allo.). If the likelihood that a participant would start at any of the 8 targets was equally distributed, then the expected occurrence of starting at any one target would be 12.5%. However, in each condition, there was always one target that participants began their movements more than 50% of the trials. Therefore, statistics were not needed to determine the preferred starting location during each condition. The data was extracted from the recordings of measured on touchscreen program. All twenty-six participants reach data was used in the analysis. Occasionally a glitch occurred on the screen whereby participants had to tap the target again. The first tap was recorded on the log stored by the Unity program and that is the result that was used for the analysis.

Direction of Movement

Direction of movement was analyzed using SPSS software. Participants used both their left and right hands to complete the experiment (i.e., independent variables). The second dependent variable related to task performance was percentage of trials that were performed in a clockwise direction. Since it was believed that only the hand being used to perform the task would affect the direction of movement, target orientation and reference frame were collapsed. A paired t-test was performed for the direction of movements to compare the percentage of trials that participants moved in a CW direction using both left and right hands. The mean value of percentage movement in the CW direction was extracted from SPSS for both the preferred and non-preferred hand. Each of the twenty-six participants behaviours were examined in the analysis of percentage of trials performed in a clockwise direction. Occasionally a glitch occurred on the screen whereby participants had to tap the target again. The first tap that participants made to whichever target experienced the glitch was recorded on the log stored by the Unity program, and that is the result that was used for the analysis.

First Fixation

First fixation was analyzed using the statistical software, Jamovi. Participants' gaze behaviours were analyzed by viewing recorded videos, frame by frame, to determine gaze location and duration for each trial. The first dependent variable for gaze behaviour was gaze location on the starting target. First fixation location was identified by viewing recordings taken on the gaze tracking device. We also measured the amount of time (in ms) that gaze was located at this specific initial target prior to the participants tapping the initial target (i.e., first fixation duration). Repeated measures analysis of variance (rmANOVA) was performed to determine whether the independent variables: 1. hand preference (P vs. NP), 2. frame reference (ego vs. allo); and/or, 3. target orientation affected first fixation. First fixation duration was found by calculating the mean from the mean difference obtained in the statistical analysis. The standard error value was used to calculate the standard deviation of the participants first fixation. Only twenty-one out of the twenty-six participants' gaze data was available for analysis as some of the trials gaze data did not record for five participants, therefore, those trials were removed for the analysis.

Inter-Target Gaze Shift Duration

Inter-target gaze shift duration was analyzed using SPSS software. The second dependent variable was the amount of time (in ms) that gaze was located on a particular target prior to the participants tapping that target after having tapped the first target (i.e., inter-target gaze shift duration). The first fixation was not included in this analysis, as first fixations were analyzed separately (as discussed above). Inter-target gaze shift duration was found as the mean value obtained in the statistical analysis. The standard error value was used to calculate the standard deviation of the participants Repeated measures analysis of variance (rmANOVA) were performed to determine whether the independent variables: 1. hand preference (P vs. NP), 2. frame reference (ego vs. allo); and/or, 3. target orientation affected inter-target gaze shift duration. Only twenty-one out of the twenty-six participants’ gaze data was available for analysis as some of the trials gaze data did not record for five participants, therefore, those trials were removed for the analysis.

3. Results

Performance on the reach and sequential tapping behaviours were analyzed across the twenty-six participants; however, gaze analyses were only available for twenty-one of the participants due to technical difficulties with capturing gaze behaviours of five participants.

3.1 Initial Tap

Results indicated that orientation of the ellipse had an influence on participants' behaviours. In each condition (P-allo; NP-allo; P-ego, NP-ego), when the vertical ellipse was presented, the majority of initial taps occurred at the target closest to the participants' midline (P-Ego: 74%, (Figure 3.1); NP-Ego: 70%, (Figure 3.2); P-Allo: 72%, (Figure 3.3); NP-Allo: 67%, (Figure 3.4)). In the horizontally-oriented ellipse conditions, participants tapped the target closest to their midline, followed by the target parallel and furthest from their midline (P-Ego: 70% (Figure 3.1); NP-Ego: 75% (Figure 3.2); P-Allo: 65% (Figure 3.3); NP-Allo: 61% (Figure 3.4)). When the ellipse was rotated leftwards, participants reached to the target that was along the long axis closest to their midline, regardless of reference frame or hand (P-Ego: 72% (Figure 3.1); NP-Ego: 64% (Figure 3.2); P-Allo: 54% (Figure 3.3); NP-Allo: 61% (Figure 3.4)). Similar results were observed when the ellipse was rotated rightwards (P-Ego: 58% (Figure 3.1); NP-Ego: 67% (Figure 3.2); P-Allo: 65% (Figure 3.3); NP-Allo: 58% (Figure 3.4)).

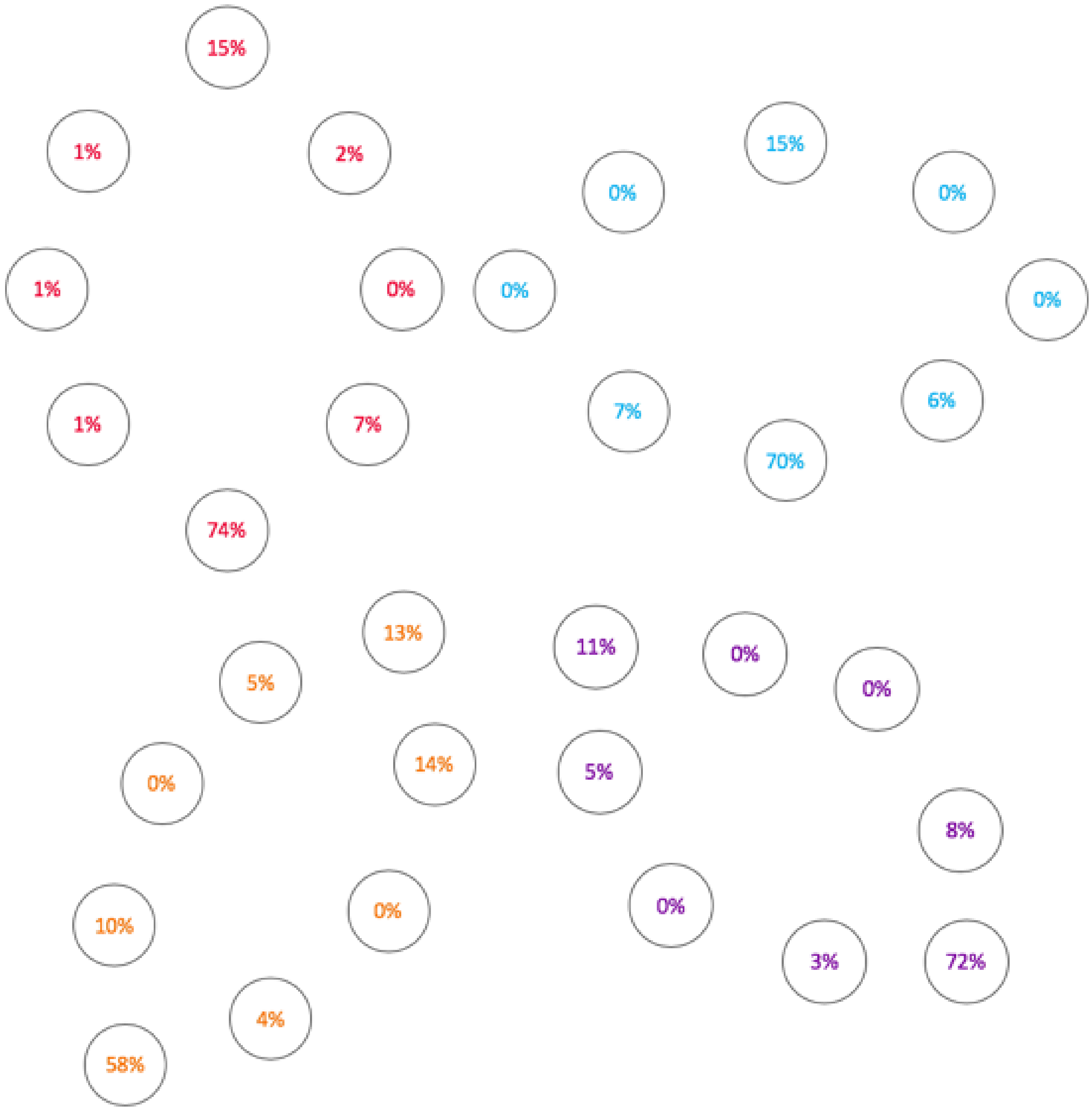


Figure 3.1. Percentages of initial target tapped in the preferred-egocentric condition.

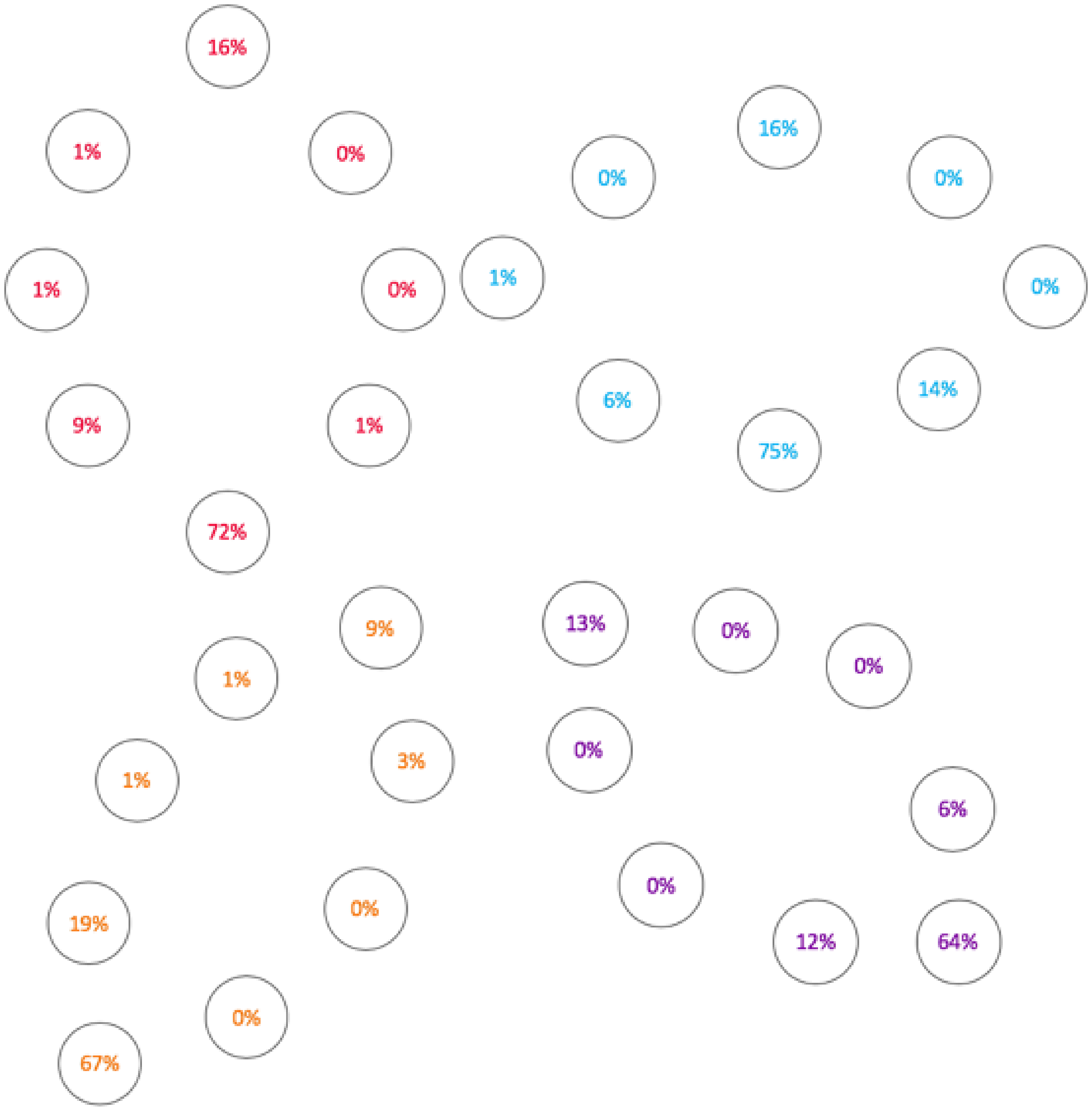


Figure 3.2. Percentages of initial target tapped in the non-preferred egocentric condition.

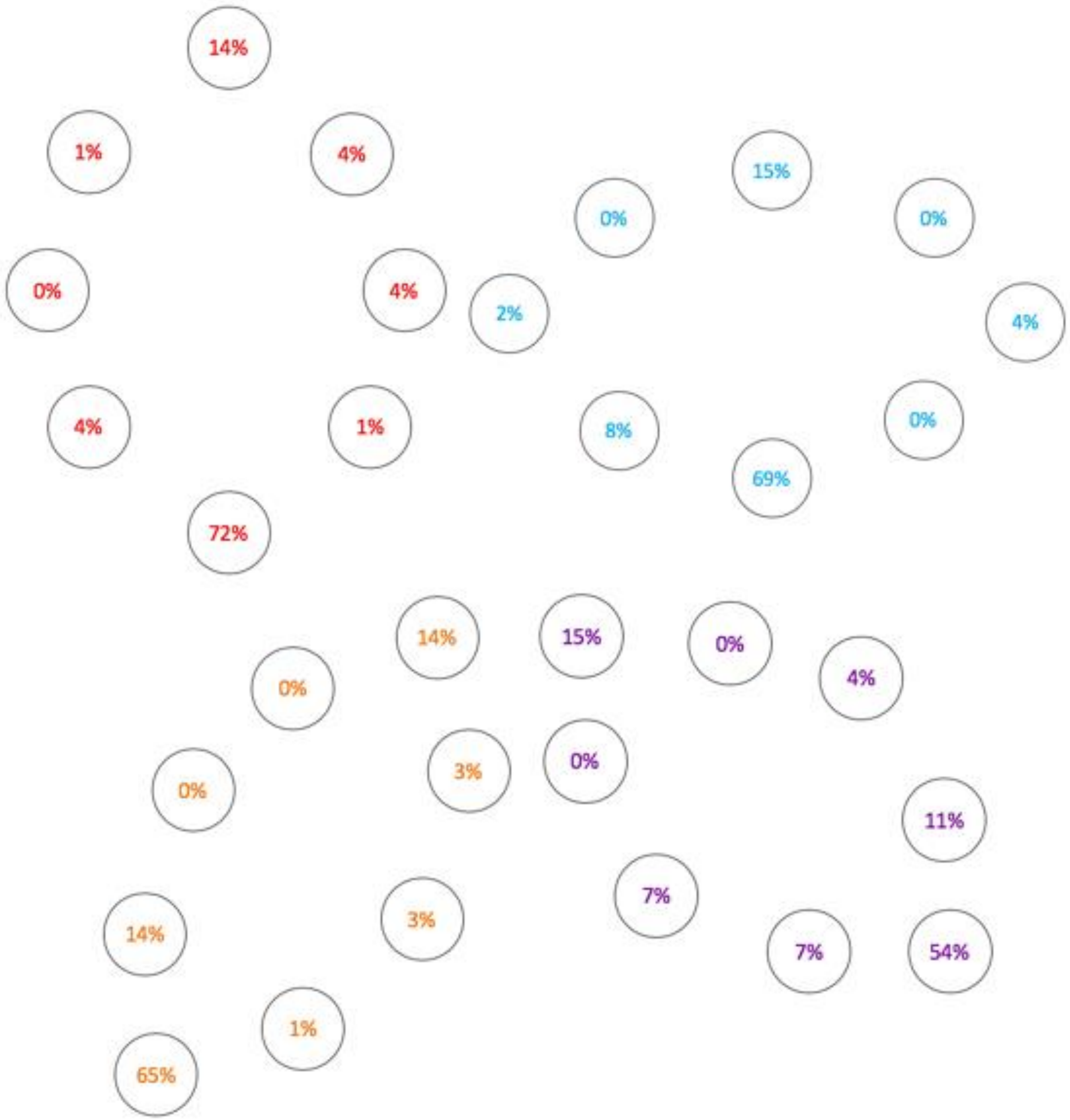


Figure 3.3. Percentages of initial target tapped in the allocentric preferred condition.

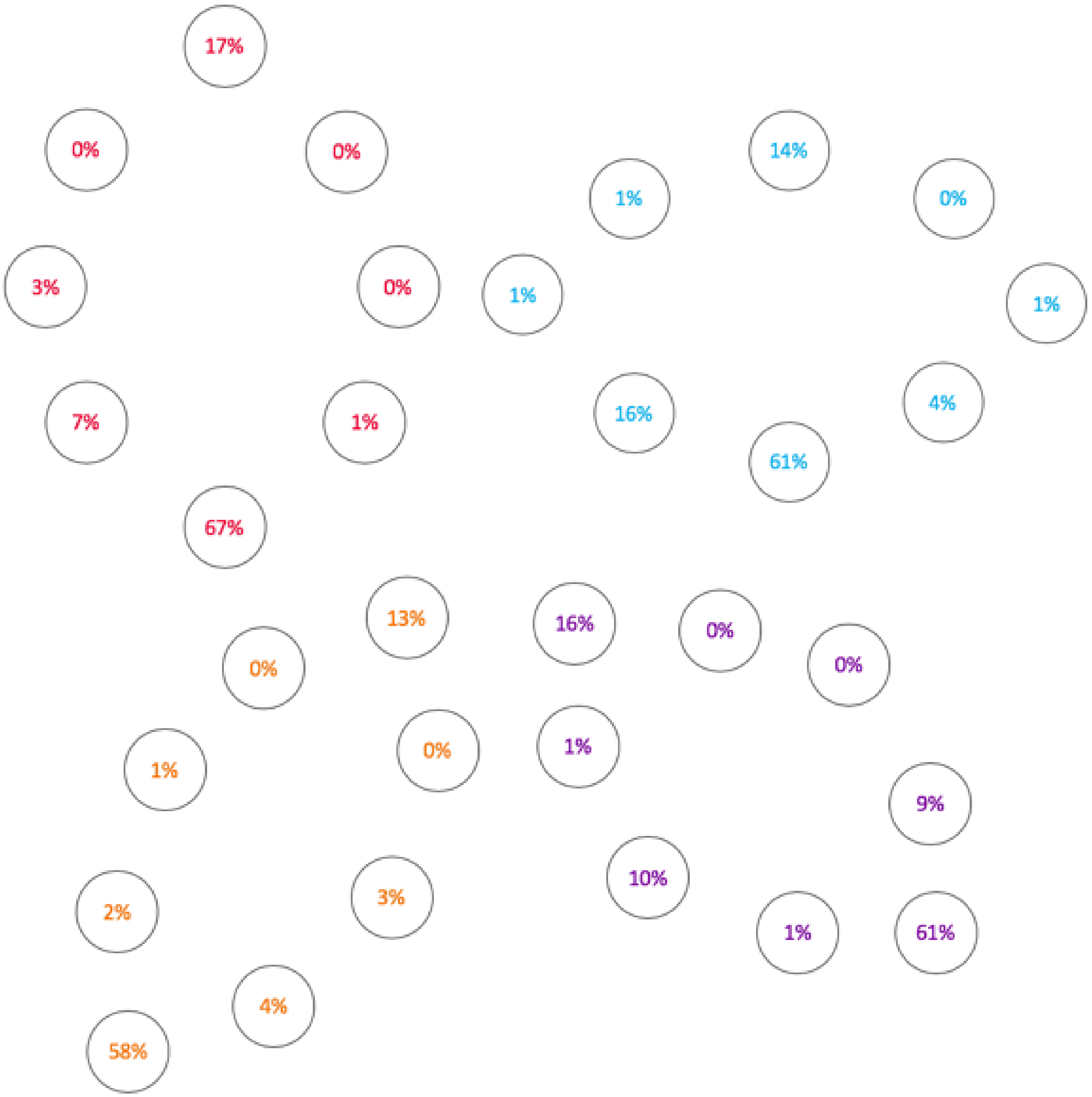


Figure 3.4. Percentages of initial target tapped in the non-preferred allocentric condition.

3.2 Direction of Movement

The paired t-test revealed that the proportion of trials in which participants moved in a clockwise (CW) direction was not significantly different between preferred (68%) and non-preferred hands (71%), *t*(21)=-0.344, p=.73. Participants were just as likely to move in the clockwise direction with the preferred hand as the non-preferred hand.

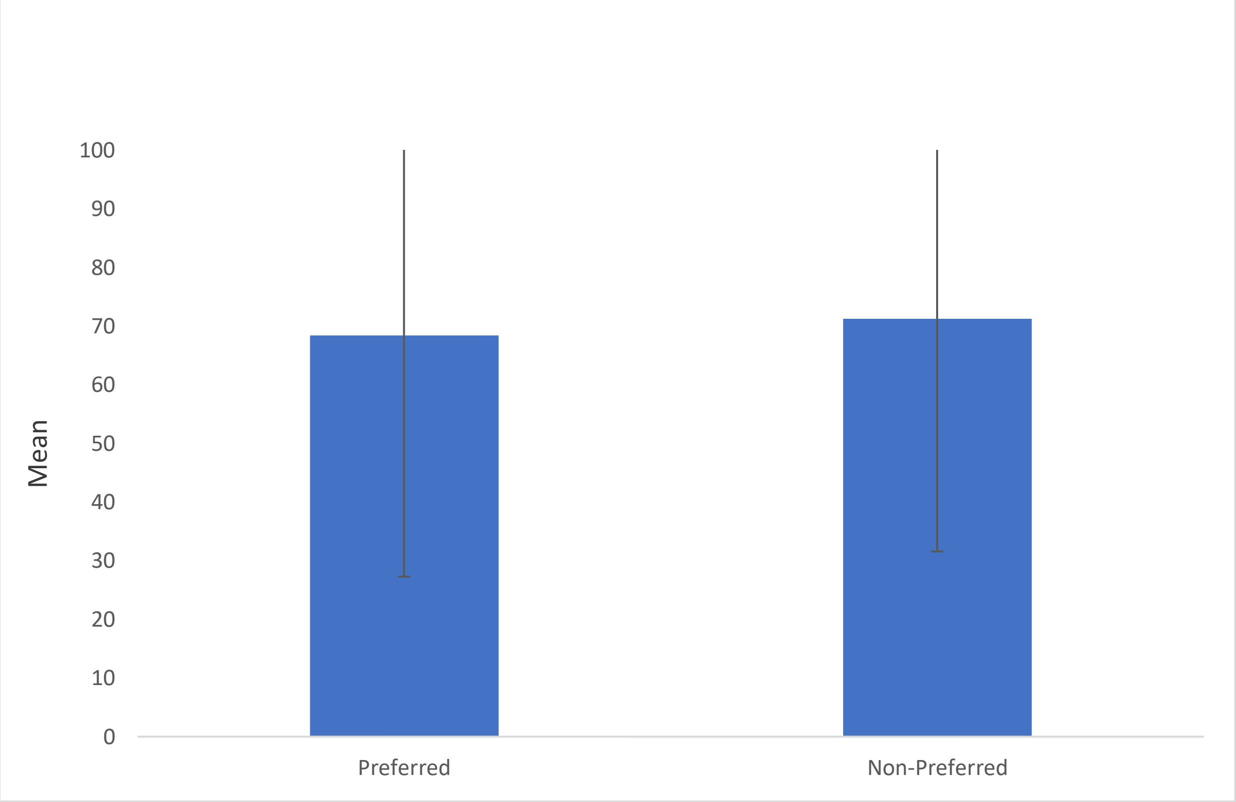


Figure 3.5 – The mean (CI 95%) direction of sequence completion in both the preferred and non-preferred hands.

3.3 First Fixation

A repeated measures ANOVA indicated a main effect of hand preference ($F_{(1, 20)}$=5.85, p<.05, f=0.23), where the preferred (P) hand (M=186 ms, SD=13.01) was accompanied by longer first fixation durations than the non-preferred (NP) hand (M=178 ms, SD=13.01). The results revealed a main effect of orientation ($F_{(1, 20)}$=3.15, p=0.03, f=0.136) on first fixation duration. The leftwards orientation (M=179 ms, SD=20.94) and rightwards orientation (M=177 ms, SD=20.94) had shorter first fixation durations than the vertical (M=187 ms, SD=20.94) and horizontal orientations (M=189 ms, SD=20.94).

Findings from our study indicated that eye movements are made prior to reaching movements in a sequence task. Participants demonstrated brief visual scanning of the screen and targets, however recording only began once participants fixated on their first target. However, they fixated only upon the initial target prior to tapping.

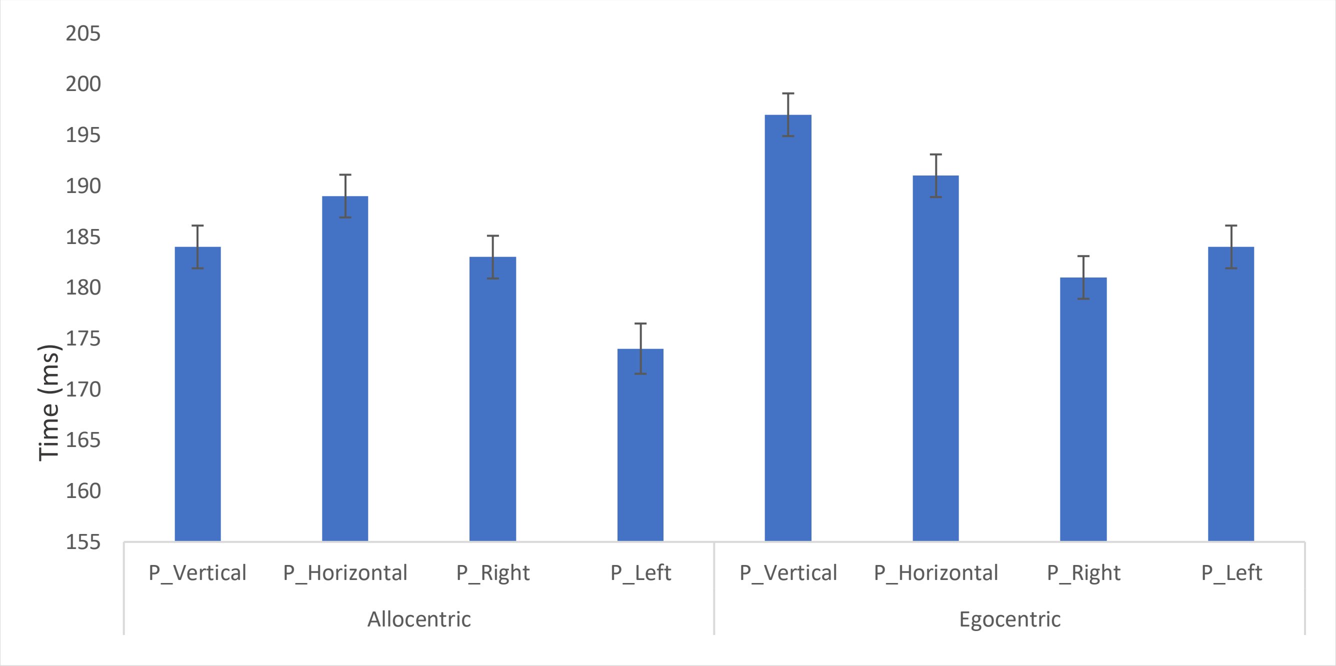


Fig. 3.6 - Participants' average fixation duration on the first target prior to reaching in the preferred hand condition.

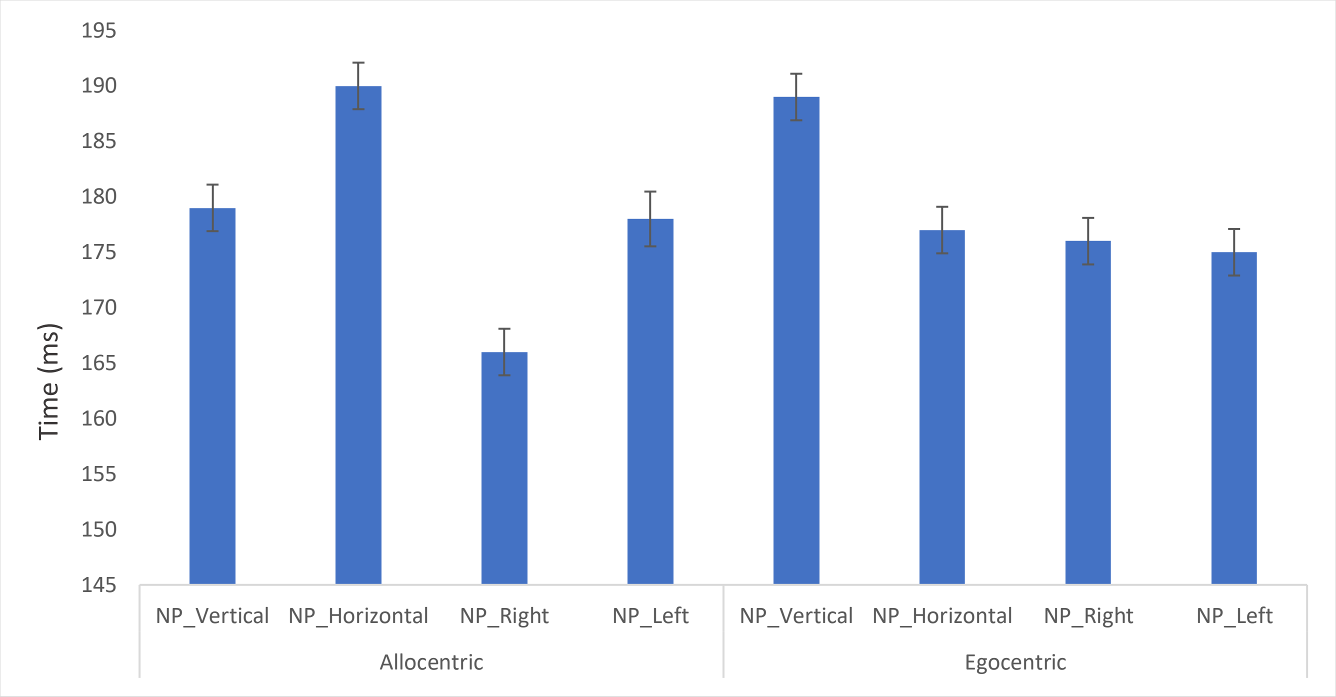


Figure. 3.7 - Participants' average fixation duration on the first target prior to reaching in the non-preferred hand condition.

3.4 Inter-Target Gaze Shift Duration

Gaze behaviours preceded finger tapping in the same order that reaching movements were made. Analysis of inter-target gaze shift duration revealed a single main effect of reference frame on gaze shift duration ($F_{(1,20)}$=.42, p=.20), such that gaze shift duration did not differ significantly between the allocentric conditions (M=69.29 ms, SD=13.52) and egocentric conditions (M=68.15 ms, SD=15.5). There was no main effect of hand preference on fixation length ($F_{(1, 20)}$=.895, p=.355) whereby duration did not vary significantly between the preferred hand (M=68.05 ms, SD=14.07) and non-preferred hand (M=69.39 ms, SD=14.62).

Findings from our study, eyes directed the hand towards each consecutive target, with the eyes leading by approximately 70 ms between targets. Average inter-fixation durations were: P_allo: 68.1 ms; P_ego: 70.2 ms; NP_allo: 71.2 ms; and NP_ego: 68.9 ms.

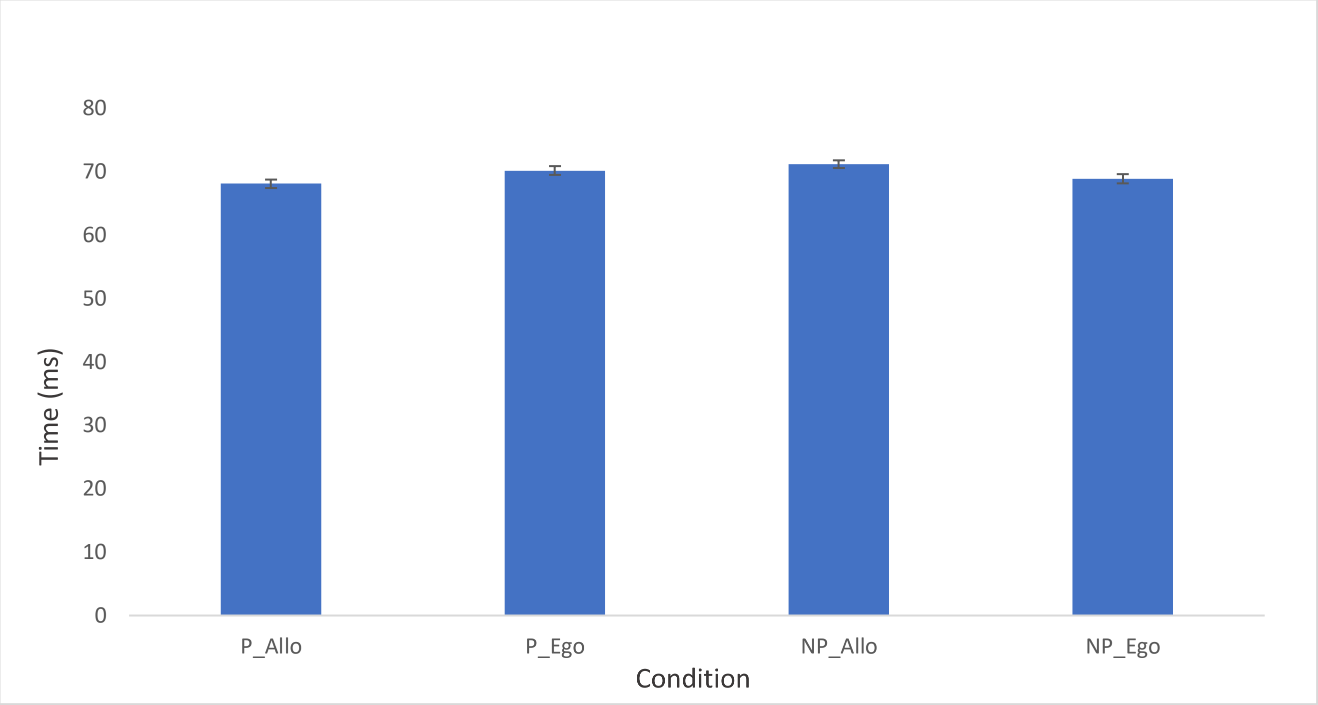


Fig. 3.8 - The mean duration of inter-target gaze shifts for preferred allocentric condition, preferred egocentric condition, non-preferred allocentric condition, and non-preferred egocentric condition.

4. Discussion

The objectives of the current study were to investigate the order of reaching and gaze behaviours of young adults during a sequential tapping task using allocentric and egocentric reference frames. It was hypothesized that: 1) the reach component of the movements would be influenced by frame of reference, such that in the allocentric reference frame participants would begin the task at the furthest point away from their body; using non-body related visual information to guide their hand to their first target (Chapelain et al., 2012); 2) the direction of movement would be influenced by the hand performing the task, such that the sequence would be completed in the clockwise (CW) direction with the right hand (Franz, Rowse, & Ballantine, 2002) and the counter-clockwise (CCW) direction with the left hand (Scheirs, 1990); 3) participants would fixate the initial target to be tapped in the sequence just prior to the movement (Hayhoe, 2000); and 4) participants would move their eyes towards each target in the sequence prior to tapping that target (Herst, Epelboim, Steinman, 2001; Hayhoe, 2000).

4.1 Initial Tap

One of the primary hypotheses of the current study was that participants would begin the task at the target closest to their resting hand during the egocentric reference frame, using the visual reference of their resting hand to guide their initial reach. When a direct limb-target comparison is available initial movements are typically made in proximity to the target closest to the limb (Musalek, Scharoun, & Bryden, 2016; Neely et al., 2008). However, the results from the current study revealed that participants were more likely to begin the task at the target closest to their midline (when presented with the vertical and horizontal orientations), or at the long axis closest to their midline (when presented with the leftwards and rightwards orientations), regardless of the reference frame. The role of the dorsal visual pathway in the online control of movement may explain why participants did not use the resting hand as an egocentric reference frame. The posterior parietal cortex (PPC) has been shown to be important for online control of movement (Fattori et al., 2005). The PPC controls goal-directed movements that are mediated by egocentric visual information (Krigolson & Health, 2004). It is possible that participants in the current study did not begin the task at the target closest to their resting hand because absolute comparisons were made between the limb in action (not the resting hand) and the target in order to support visuomotor behaviours in the dorsal visual pathway (Neely et al., 2008). The resting hand was not within the visual display of the touchscreen or targets during the allocentric condition. Therefore, it was thought that participants would rely on background information, rather than resting hand (which was out of visual view by resting on their thigh), to guide their actions because in the allocentric condition, visual information of the limb was not readily available to them (Neely et al., 2008).

One explanation for the findings, is that participants may have used their centre of mass (located near their navel) as an egocentric reference frame to guide their movements throughout the task (Pesaran, Nelson, & Anderson, 2006). Guiding their movements in this way was not due to reference frame, but rather because movements that are made closer to the midline require less energy expenditure and less time to execute (Roberts, Burkitt, Elliot, & Lyons, 2016). In peripersonal space, moving from a position closer to the body towards a position away from the body is more favourable compared to beginning the task further away and moving back towards the body (Forsyth, Puckering, & Bryden, 2015). Visually-guided goal-directed movements are controlled by the egocentric frame of reference (Goodale & Milner, 2004); and it is the moving hand and target that ultimately form this egocentric reference frame (Neely et al., 2008). Therefore, it can be argued that participants chose to begin the task closer to their centre of mass where the moving hand began the task because of this egocentric reference frame, as well as a movement made closer to the body being less costly than one made further away (i.e., a movement beginning at the target closest to the resting hand). Initial movement planning aims for minimal online corrective processes during movement execution and for optimizing movement time and energy expenditure (Roberts et al., 2016). When reaching towards the target closest to the midline, movement distance is within peripersonal space and not far from the initial starting position. Therefore, the initial reach requires less time, less energy expenditure, and is less likely to undergo corrective movements as the reach and tap is performed (Roberts et al., 2016). In this sense, participants in the study might have taken the most convenient and efficient route by reaching to the target directly in front of their midline as to reduce error and timing of the task. Had participants reached to a position further away from their body first it is possible they would have been more likely to overshoot the target. Overshooting increases travel distance and forces muscle groups to switch roles (i.e. agonist becomes antagonist and vice versa) (Elliot, Hansen, Mendoza, & Tremblay, 2004). An overshoot would have been more costly, increasing potential error during the trajectory and requiring greater energy expenditure. Since the CNS is capable of planning movements ahead of time based upon the most convenient action available to the individual (Cos et al., 2011), initial taps reflected the simplest and most efficient routes.

As mentioned in the Chapter 2, the moving hand started the task at a position directly in front of the body’s midline. The centre of mass may have caused participants to take a more efficient route as described above, however, it is most likely that participants used their moving hand in its initial position for each trial as a reference frame, regardless of the condition. In situations where the moving limb is visible, individuals tend to create an egocentric reference frame between the moving limb and target (Neely et al., 2008). Furthermore, egocentric reference frames are often used to control movement within the peripersonal space (Forsyth et al., 2015). Participants might have created a frame of reference between the moving hand and initial target, since it has been found that they are most likely to tap to a target that is both within a close proximity to that hand, and within their field of view. Visual information in the lower field of view (i.e. the location of the start position) shows a bias towards creating faster and more accurate pointing movements (Danckert & Goodale, 2001). Therefore, it is believed that the role of vision and starting placement of the moving hand caused a reference frame to be formed at the starting position that was within their lower field of view.

It was hypothesized that the long axis would affect reaching behaviours in the allocentric condition. The results revealed that in all orientations, except the horizontal orientation, participants began the task at the long axis that was closest to their midline. These findings are consistent with previous literature examining targets being presented at different angles and orientations, whereby movements are made to a target that appears as a protruding element (Roberts et al., 2016; Johansson, Westling, Backstrom, and Flanagan, 2001; Chun, 2000). The target at the long axis might have been an attention-directing cue (Chun, 2000) in peripersonal space, essentially drawing the eyes to this target, and later the arm and hand.

4.2 Direction of Movement

Since the targets were presented in ellipse-shaped orientations, it was expected that they would be treated and acted upon similar to circle drawing tasks, which is to move in the clockwise direction with their right hand, and the counter-clockwise direction with their left hand (Chapelain et al., 2012; Franz, Rowse, Ballantine, 2002; Taguchi & Noma, 2005). However, the results from the current study revealed that participants were just as likely to move in the clockwise direction with their left-hand as they were with the right-hand. The discrepancy between the expected and the observed findings could be due to: 1) the fact that participants were asked to complete a sequential tapping task (series of discrete movements) and not a drawing (i.e., smooth continuous) task; and/or 2) the order of performance.

The nature of the task may account for why participants moved in similar directions when using either the left or right hand. Perhaps dissimilar to circle-drawing tasks, the left hand did not exhibit a preference for moving in the counter-clockwise direction (nor the right hand in the clockwise direction) because the task was most similar to a discrete movement tapping task. During a visually-guided tapping task gaze modulates the direction in which reaches will be performed (Baker, Donoghue, & Sanes, 1999). In the sequential task performed, participants demonstrated this phenomenon to look before tapping. Neurophysiology research suggests that neurons of the superior parietal cortex (SPC) monitor arm-target interactions in peripersonal space specific to the direction of gaze and the limb (Fattori et al., 2005). After the direction for which the limb should move is decided upon, a population of neurons in M1 activates to move the limb to the desired target when the reach is being executed; these neurons are also direction specific (Georgopolous et al., 1986). Evidence investigating the direction of movements in right-handed individuals during a pointing task suggested that the left hand is more susceptible to modifying movement direction during task execution (Boulinguez, Nougier, & Velay, 2001). As participants completed each trial, they experienced short-term practice of the tapping skill. During short-term practice of a tapping skill, constant repetition leads to short-term cortical reorganization defined by a more efficient network for the specific trained movement direction (Morgen et al., 2003). This is contrary to circle-drawing tasks whereby visual scanning biases might be present (i.e., biases that are similar to how an individual might read or write), influencing the limb to move in the direction of those biases (Faghihi, Garcia, & Vaid, 2018;

Taguchi & Noma, 2005). There may have been an equal likelihood of participants moving in the clockwise direction with the left and right hands because the transfer of information between hemispheres chose one more efficient route of direction to complete this novel task. In addition, an imperative difference between a circle-drawing task and the current tapping task is that in circle-drawing tasks a tool, such as a pen, or a stylus is regularly used. When using a stylus, kinematic changes may occur about the wrist and finger, causing constraints in drawing behaviours, compared to when drawing without a stylus (Van Emmerik & Newell, 1990). A stylus affects tends to affect the coordination of the wrist and hand, and therefore elicits behavioural changes to drawing with the finger itself (Dounskaia, Gemmert, & Stelmach, 2000). Since participants were practicing a new skill, and were using their finger, and not a tool, it is argued that the nature of the task (i.e. discrete tapping task) more likely influenced the direction of movement, rather than their scanning behaviour.

Another possible explanation as to why the direction was similar between the hands might be due to the order of the hand performing the task (in this task, the right hand always went first). The current evidence on handedness and direction of movement shows that right hand dominant individuals typically perform movements in the clockwise direction with their right hand (Mouloua et al., 2018). For example, when turning a doorknob, right-hand dominant individuals tend to turn the knob clockwise (Brebner & Sandow, 1976). Furthermore, when performing a task with the right hand, whether an individual is right-hand dominant or not, similar behaviours are observed between the hands (Mouloua et al., 2018). This suggests that when participants perform a movement in a specific order or direction with their right hand first, the left hand mimics the behaviours of the dominant hand. Since the participants in this study always performed the task with the right-hand first, participants may have become accustomed to moving in the clockwise direction with both hands. When Mouloua and colleagues (2018) investigated handedness on a motor task using a mouse-pointing task, they examined both left- and right-hand dominant individuals to illustrate any differences in aiming behaviours. Their findings support the results of the current study. First, they found that both left- and right-handers demonstrated similar motor performance when they completed the task with the right hand. Second, they suggested the right-handers produced movements with less variability and more consistency with their aiming behaviours than left-handers because of their prior degree of training (i.e., right-handed mice are much more commonplace than left-handed mice). Finally, they argued that within-subject differences might be less pronounced if participants are not exposed to the task with their dominant hand first. A study by Ghilardi, Gordon, and Ghez (1995) support this idea as they found a directional bias of movement depending on the location of the starting position of the hand. It was discovered that hand path planning is determined by actual initial position of the hand and where the brain interprets the location of the starting position. Specifically, if the brain interprets the arm as being closer to the midline (as opposed to being closer to the left or right of the midline), or being to the right of the midline, then the arm will move in a clockwise direction. A counter-clockwise directional bias would only occur if the initial position was interpreted as being to the left of the midline (Ghilardi, Gordon, & Ghez, 1995). Therefore, it’s possible that participants were affected by where they began the task relative to their midline. Which hand begins the task may be an important factor to consider in the future with this task as the starting position was not made consistent during this experience. Those right-hand dominant participants beginning the sequence with the right hand might have affected the direction of their movements by influencing the left-hand to follow suit, moving in the clockwise direction. As a result, in the current study there was no effect of the hand performing the task on direction of movement observed because the participants were just as likely to move in the clockwise direction with their left hand as their right hand.

Ultimately, it is believed that participants configured the most methodological way to complete the sequence in this study by replicating the movement pattern that was done with their right hand with their left hand. However, and to a lesser degree, an argument could be made based on the idea that in Western society we are used to reading and writing from left to right, and therefore choose to move in the left to right direction (De Agostini et al., 2011); this bias appears to be even more pronounced in right-handers (Faghihi, Garcia, & Vaid, 2019). However, the degree of manual asymmetry varies between tasks (Hausmann, Kirk, & Corballis). This argument suggests that handedness is a product of genetics, social pressure, behavioural traits (such as lateralized practice), and neural asymmetries (Marcori, Monteiro, & Okazaki, 2019). Social pressures can produce a leftwards-to-rightwards shift in hand preference (Meng, 2007). As such, it is possible participants might have felt an obligation to perform similarly with their left hand as they would with their right hand because one of the study's participation requirements was being right-handed. However, it is more likely that the left hand mimicked the actions (direction) of the right hand due to the dominant hand performing the task first (Mouloua et al., 2018). As such, handedness and the direction of movement should be further investigated while completing sequence-type tasks in left- and right-handers; as well as when performing the task with the non-dominant hand first.

4.3 First Fixation

Previous research demonstrates evident coupling between eye movements and upper limb movements (Land, 2006; Horstmann & Hoffmann, 2005). Most of our daily activities involve synchronous movements in which vision and action are tightly coupled. In visually-guided tasks, it is thought that the CNS prepares the eyes to move prior to initiating a movement of the hand based on spatial representations (Schenk, 2006). Typically, the eyes tend to seek out information from the environment in the instances before each action commences (Land, 2006). Spatial priming is a visual search phenomenon whereby reference frames are used to code the location of an object as a way of bringing the hands to the target (Ball et al., 2010). The results from the current study corroborate with the body of literature suggesting that the eyes guide the hand to action. Similar to Hayhoe (2000), we found that the eyes move prior to the arm acting upon the initial target. Before the next arm movement is made, a shift in gaze occurs bringing the eyes to the next target in the sequence. It is believed that a spatial code is formed in visually-guided tasks between the environment (i.e. allocentric), eyes and/or body (i.e. egocentric), and a target as to guide the hand towards an object of interest (Pesaran, Nelson, & Andersen, 2006).

Since visual information influences the decision-making process relative to movement creation (Ballard, Hayhoe, Li, & Whitehead, 1992), there are three potential possibilities to explain the findings from the current study. First, results from this study revealed longer first fixations occur when using the right hand to complete the task. Evidence suggests that the right hand-left hemisphere system requires less time to process visual information about a targets location in space prior to initiating a saccade towards the initial target (Schmitz et al., 2019; Roy et al., 1994). This hemispheric asymmetry in visuomotor processing has demonstrated to influence movements causing specific advantages for actions depending on the hand in use. The right hand-left hemisphere system has also demonstrated to be more efficient at processing visual and non-visual information as it may require less information from the environment to base one’s movements and to detect and correct errors (Roy et al., 1994). In this study, initial fixation duration was measured as the length of time between fixating to tapping the first target. The results of the current study are not supported by the literature as the right hand required more time than the left hand to move to the first target after fixation. However, perhaps the left hemisphere is more dominant than the right hemisphere for cognitive motor-processes, such as construction and storage of motor programs, using sensory feedback to monitor movements, selecting and retrieving motor programs for sequential movements, and ordering sequential processes (Haaland & Harrington, 1996). Therefore, the storage and retrieval of motor programs could explain the behaviours observed in this study; however, since this is a simple task it can be argued that a motor program would not be necessary or may not exist for the given task (Haussman et al., 2004).

Another explanation as to why the right hand may have experienced a longer first fixation is because participants were given minimal instructions on how to perform the task. Participants were told they were allowed to choose the initial target location. It is possible that participants may have based their initial fixation on an eye-hand reference frame because the task was performed within their peripersonal space (Pesaran, Nelson, & Anderson, 2006). Visual information about a limb’s position in space travels from the visual cortex, to the posterior parietal cortex (PPC), and finally to the frontal lobe where the decision-making process occurs (Batista, Buneo, Snyder, & Anderson, 1999). In the PPC, the parietal reach region (PRR) can plan movements based on a coordinate system made between the eyes and limb (Batista et al., 1999). Therefore, a reference frame may have helped coordinate the initial movement between the eyes and both hands (Pesaran, Nelson, & Anderson, 2006). Right-handed (left-hemisphere dominant) individuals typically experience greater transfer of advanced planning during visually-guided goal-directed movements after practice than left-handers (Lavyrsen et al., 2003).

Therefore, the left hand might have experienced shorter fixations because participants had practiced moving within the established reference frame previously with their right hand.

The third, and most likely explanation for the pattern of results, is the order in which participants performed the task accounts for the difference in fixation durations. It is possible that because the right hand always began the task, the right hand required extra time to solve the problem to create and refine the solution; and, in return, the left hand benefitted from this process by requiring less time to process visual information. The left hemisphere is more dominant at using sensory feedback to monitor movements, therefore, the right hand may have experienced a delay in the time between fixating and moving towards the first target since 1) The right hand was always used first for each participant causing an increase in fixation time as a result of greater cortical processing post-fixation as participants processed the orientation of the targets. Starting the task with the right hand may have caused an increase in the length of time until first fixation as both the task itself and the coinciding target orientations were novel for the right hand and not the left hand (Baso & Wurtz, 1997); and, 2) The reference frame may have been defined by the left hemisphere after initial saccadic activity determined how the hand should perform the task. The latter might require additional processing of the left hemisphere to ensure for accuracy and efficiency of the movement post-visual integration (Schluter, Krams, Rushworth, & Passingham, 2001).

The orientation of targets may have also influenced the duration of first fixation. When the targets were presented in horizontal and vertical orientations, results revealed that participants fixated longer than they did in the diagonal orientations. Participants in this study seemed to base their reach towards the initial target based upon where they were looking prior to acting. In monkeys, the premotor dorsal cortex (PM_d) has been found to contain neurons that encode for the target, hand, and eye in a relative spatial position. As such, spatial position is important for coordinating eye and hand movements (Pesaran, Nelson, & Anderson, 2006). With regards to participants' reaching behaviours, it was hypothesized that the long axis would affect the target that participants initially reached towards, specifically the long axis affecting behaviours in the allocentric condition, and the target closest to the resting hand during the egocentric condition. The observed gaze behaviours demonstrated that prior to reaching to their first target, participants fixated first on that target. Although the hypotheses related to the reach movements during the task were found to be incorrect, participants may still have used spatial coding to establish where to begin the task; and it is possible that in the horizontal and vertical orientations, participants may have required more processing time to establish a reference frame because of where the initial target of choice was located (Pesaran, Nelson, & Anderson, 2006). The long axis closest to the midline of the diagonally-oriented ellipses may have directed participants' attention, drawing their eyes to fixate earlier on this target, thereby decreasing the amount of time between first fixation and moving the arm towards the initial target. Current literature suggests that people tend to more efficiently focus their attention in a “rich” quadrant of the reference frame (i.e. an area that more frequently contains a target) compared to a more “sparse” quadrant of the reference frame (i.e. an area with less potential for a target) (Jiang & Swallow, 2013). Research shows that orientation, specifically, the angle of an object, provides a visually-drawing directing humans attention (Chun, 2000). Extending upon this idea, Johannson and colleagues (2001) found that in a natural reaching task (i.e., reaching and grabbing a bar), participants fixated upon the tip of the bar, or a “protruding element” of the object to direct their gaze, and then their movements in a more timely and efficient manner. Therefore, the long axis point closest to the midline in the diagonally-oriented ellipses may have appeared more attention-grabbing to participants, thereby reducing the length of cognitive processing prior to fixation because there was: 1) a greater likelihood of target appearance in the reference frame at the long axis point, therefore increasing the likelihood of attention to this area (Chun, 2000); and 2) the long axis was a focal point in the environment drawing gaze towards the target in the diagonally-oriented ellipses (Johansson, Westling, Backstrom, and Flanagan, 2001).

There has also been evidence to suggest that a bias of using visual information from the lower field of view occurs in pointing tasks. Specifically, when performing a pointing task with a finger, the dorsal visual stream seems to guide actions more quickly and accurately within the lower field of view (Danckert & Goodale, 2001). The lower visual field appears to be more engaged when performing tasks in the peripersonal space, whereas the upper field of view processes more information in the extrapersonal space (Danckert & Goodale, 2001). As such, there appears to be an overrepresentation of the lower visual space when performing a pointing task that is within the peripersonal space. These findings are in agreement with this study, whereby participants initially fixated towards targets that were within the lower visual field.

4.4 Inter-Target Gaze Shift Duration

Gaze shifts were expected to occur on a continuous basis as the sequence was completed. When vision is available to people during a sequence-based task, it has been found that people will shift their eyes from one goal to the next before performing a reaching movement (Land & Hayhoe, 2001). The results of this study agree with the aforementioned literature as the eyes lead the hand to each consecutive target in the sequence, with a stable gaze lasting on each target for approximately 70 ms prior to tapping. When examining coupled eye-hand movements there are specific regions of the PPC related to both the looking component of the task and where one will reach (Horstmann & Hoffman, 2005). As mentioned in Chapter 1, the PPC contains the lateral intraparietal area (LIP), which hosts neurons responsible for initiating eye movements towards intention-driven visual information; and the parietal reach region (PRR), which plans for reaching movements (Batista & Anderson, 2000). These areas within the PPC work together to create intention-based reaching actions relative to the visual information provided by the scene or environment (Horstmann & Hoffmann, 2005; Anderson, Snyder, Bradley, & Xing, 1997).

In natural manipulation tasks, such as Land & Hayhoe's (1999) "tea-making" investigation, or Hayhoe's (2000) "sandwich-making" study, vision typically leads the reaching and manipulation action by less than one second. While these investigations involved reaching, as well as grasping, our results showed similar a similar gaze shift duration time prior to reaching – approximately 70 ms. Further research observing gaze and reaching behaviours also supports this study's findings that gaze movements precedes reaching actions, and specifically, these gaze movements occur from one target to the next consecutive object to be acted upon (Johannson et al., 2001). More specifically, gaze has been shown to direct towards the centre of the object or the area of the object to be reached towards (Johannson et al., 2001). The observed experiment required participants to move in a consecutive order after tapping the initial target. Therefore, participants used the strategy of "look and go" to perform the task, as has been observed in previous literature. It is evident that a tight coupling between arm and eye movements exists – these results have consistently been found because once visual information about the target is retrieved, the same retinal information triggers a common pathway for eye to arm movements (Helsen et al., 2000).

4.5 Limitations

There were a few limitations to the current study. The study was completed with a smaller sample size than originally was intended, given the shutdown of research following the spread of the COVID-19 virus. A larger sample size might have revealed greater differences in reach and gaze behaviours; increasing the statistical power of the results. It would be of interest to measure left-handed participants as well as other age groups (i.e. children and older adults), to determine if results are consistent to what we found in this study and what we believe led to these findings.

In addition, this study had all participants begin the task with their right hand; there was no group of participants beginning with the left hand. The literature examining handedness suggests that the right-hand exhibits more dominancy over a pattern of aiming behaviours when performing first (Mouloua et al., 2018). As such, crucial differences might be found if one were to examine half of the participants beginning the task with the right hand, with the other half of the participants beginning with the left hand. Having this information would determine if moving in the clockwise direction was truly because the right-hand lead direction behaviours for both hands, or not.

4.5 Conclusion

The findings from the current study suggest that in a sequential tapping task, younger adults rely upon spatial reference frames to guide their behaviours. Specifically, when performing in peripersonal space, an egocentric reference frame guides a reach to tap the first target when the moving hand is closest to the body's midline (Forsyth et al., 2015), unless a protruding, salient cue is present (Johansson et al., 2001; Chun, 2000). When performing a sequence task and examining direction of movements, the right-hand, or dominant hand, typically leads, while the left-hand follows suit; however, this might be due to the right-hand performing the task first. Eye movements indicate that this experimental sequential task is similar to a natural sequence task, such as making a cup of tea (Land & Hayhoe, 1999) or a peanut-butter and jelly sandwich (Hayhoe, 200). Therefore, gaze ultimately influences reach behaviours when performing a sequence tapping task, and visual information is used in an egocentric fashion when performing in the peripersonal space.

The findings from the current study have established a baseline for performance during a sequential tapping task and gaze behaviours in healthy young adults. Future research can expand upon this study by exploring the behaviours of individuals with increased difficulty performing activities of daily living, such as children with autism spectrum disorder (Larson & Mostofsky, 2008) and older adults (Raw et al., 2015). Specifically, older adults experience greater difficulties performing activities of daily living (Azad et al., 2017), and therefore, might demonstrate poorer performance in this task.

The use of this task might also be useful to researchers and clinicians in rehabilitating post-stroke or post-traumatic brain injury patients, as the results have shown that there is a behavioural transfer of information between left and right hands when manipulating reference frames. Perhaps training the limb on an unaffected and non-damaged hemisphere might cause increased interhemispheric connections to form, allowing the affected limb to acquire the benefits. Studies have investigated training techniques to an unaffected limb post-stroke that have resulted in organizational changes within the cortex (Pruitt et al., 2017). The egocentric cues present in this study might elicit behavioural changes that extend upon previous rehabilitation methods, as has been found with patient D.F. Overall, this sequential task using alternating hands and reference frames might prove to have developmental, as well as clinical practical applications.

Chapter 5: Infographic

Understanding Reaching Movements in a Sequential Tapping Task

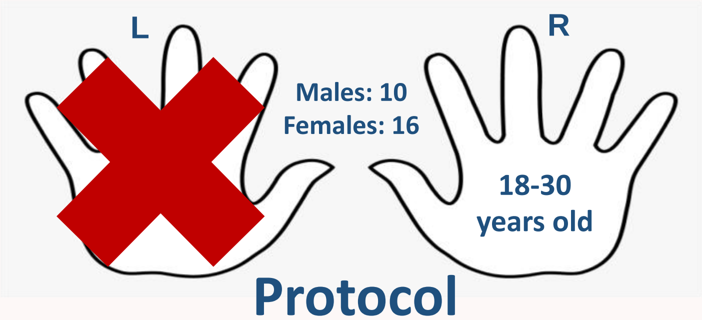
What we did:

Using a touchscreen, participants were asked to tap and extinguish a series of targets presented in five different orientations in a consecutive order. Individuals were able to choose where to start tapping, and which direction to move.

Why we did it:

Everyday we perform activities of daily living (ADLs) that require us to explore our environment and make decisions based on what we see, yet minimal work has investigated reaching and gaze behaviours in a sequence-type task.

Participants



Males: 10
Females: 16

18-30 years old

Protocol

Egocentric

Step 1:

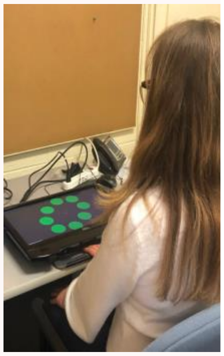
Fit participants with gaze goggles

Step 2:

Practice egocentric and allocentric hand positions

Step 3:

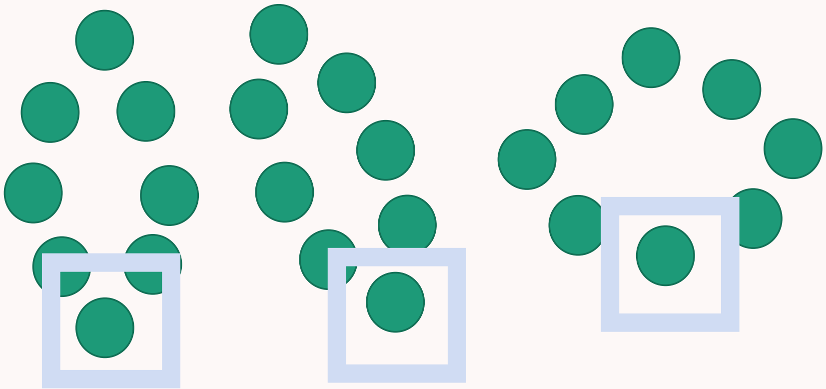
Perform a total of 60 trial, alternating hands every 15 trials (R hand begins)



Allocentric

What we found:

1. Starting target:



Always started at target closest to midline in vertical and horizontal orientations; or long axis nearest to midline in diagonal orientations

2. Direction:

Left hand just as likely as right hand to move in the CW direction

3. Eye movements

Eyes lead the hands to the first, as well as to each consecutive target

Similarities in reach behaviours between hands and reference frame suggests a transfer of information during a sequential task…

This novel task could measure the extent of visuomotor deficit in:

Autism spectrum disorder

Elderly

And be used as…

Rehab for post-stroke or post-traumatic brain injury

Appendices

Appendix A: Letter of Information

WILFRID LAURIER PARTICIPANT INVITATION

Maneuvering the Upper Limb Through Space: Investigating the Relationship Between Gaze and Reach Behaviour in a Sequence Task

Principal Investigator: Robyn Grunberg, MKin
Supervisor: Dr. Michael Cinelli, PhD
(REB#______)

Hello, my name is Robyn Grunberg and I am a Masters student in Kinesiology from the Lifespan PsychoMotor Behaviour Lab (LPMB) at Wilfrid Laurier University. I would like to invite you to participate in a study we are conducting. The purpose of this study is to examine reaching and gaze behaviours in a novel sequence task.

We will be investigating healthy young adults between the ages of 18-30 years old. This study will involve 60 reaching trials. The experiment will be completed on a horizontally-positioned touchscreen computer. You will be asked to reach and extinguish a series of circles presented on the screen as quickly as possible. You will wear a pair of Tobii Pro Eye tracking glasses to collect gaze behaviour. All information and data collected will remain confidential. The study will take approximately 30-45 minutes to complete. Participation is strictly voluntary, and you may withdraw from the study at any point in time.

Unfortunately, due to the nature of the study, if you have a musculoskeletal or neurological disorder or deficit affecting your ability to reach towards the targets, or a visual impairment that cannot be corrected to a minimum of 20/70, or are ambidextrous or left-handed, you may not participate.

By participating in this study, you will contribute to the knowledge of upper limb motor control and the effect of gaze during a sequence task. This project has been reviewed and obtained ethical clearance through the Research Ethics Board at Wilfrid Laurier University. The REB application number is ____ if you would like further information in reagrds to ethical clearance of the study itself.

Please contact myself (519-884-0710 ext. 4775, grun4640@mylaurier.ca), or my supervisor, Dr. Michael Cinelli (519-884-0710 ext. 4217, mcinelli@wlu.ca) at any time if you have any questions about the study or wish to participate.

Appendix B: Recruitment Poster

PARTICIPANTS NEEDED

Have you ever wondered how reaching for your morning coffee, or your ability to text and type are influenced by where you're looking?

Researchers in the Lifespan PsychoMotor Behaviour Lab at Wilfrid Laurier University are looking for **18-30 year-old right-handed individuals** to participate in a study examining behavioural responses of reaching and gaze in a novel task.

You will be asked to reach and extinguish a series of circles presented on a touchscreen while wearing Tobii Pro Eye tracking glasses for an overall of 60 trials. Participation is strictly voluntary, and you may withdraw from the study at any point in time.

The study will be conducted in one session and takes only 45-60 minutes!

If you have any questions or are interested in participating, please contact Robyn Grunberg (519-884-0710 ext. 4775, grun4640@mylaurier.ca), or my supervisor, Dr. Michael Cinelli (519-884-0710 ext. 4217, mcinelli@wlu.ca)

REB Approval #6331

Appendix C: Consent Form

Wilfrid Laurier University
Informed Consent Statement
Maneuvering the Upper Limb Through Space: Investigating the Relationship Between Gaze and Reach Behaviour in a Sequence Task

Primary Investigator: Robyn B. Grunberg, BAKin
Supervisor: Dr. Michael E. Cinelli, PhD
Department of Kinesiology and Physical Education

You are invited to participate in a research study. The purpose of this study is to examine reaching and gaze behaviours in a novel sequence task. The researcher, Robyn Grunberg, is a graduate student in the Department of Kinesiology working under the supervision of Dr. Michael Cinelli in the LPMB Lab at Wilfrid Laurier University.

INFORMATION

You will be asked to sign the consent form upon your arrival to the LPMB Lab (NC104) at Wilfrid Laurier University. For this study, it is important that our participants do not 1) have any self-reported musculoskeletal, or neurological disorders, deficits, or medication that affect upper limb control; 2) self-report a visual impairment that could not be corrected to a minimum of 20/70; and 3) or report being ambidextrous or left-handed according to the Waterloo Handedness Questionnaire.

Prior to the experiment, you will be instrumented with gaze tracking goggles (i.e., glasses that track eye movement). First, you will complete 4 baseline reaching trials. These baseline trials will consist of reaching and pointing towards circles presented on the screen with each hand twice. During the experiment, you will be asked to remove all the circles from a sequence by reaching and touching the circles that are presented on the touchscreen as quickly as possible. Once a circle is touched, it will be extinguished. The circles will be presented in randomized blocks of a potential 5 orientations on the screen. Overall, 60 trials will be conducted. Breaks will be permitted if required. The testing session only requires one visit to the lab and should take about 30-45 minutes to complete. This research will require 40 overall participants.

RISKS

Risks of participation would not pose any greater risk than reaching for a glass of water or typing, however you may experience muscle fatigue.

BENEFITS

There are no direct benefits to the participant, however, the findings may validate the use of a touchscreen as a reliable method for studying sequence behaviours in healthy young adults. It will provide a framework for future research on sequence tasks, such as studying special populations. It may also be used in conjunction with cortical activity testing, such as electroencephalography (EEG), to investigate active cortical areas during this novel task.

COMPENSATION

There will be no compensation for participating in this study.

CONFIDENTIALITY

Names will be removed from all data sources and replaced with code numbers in order to ensure confidentiality. The data will be stored on a password-locked computer and USB stick and will be kept in a safe location (Dr. Cinelli's lab in the LPMB Lab at WLU) until September 2020, at which time the investigator and supervisor will ensure the deletion of all files. The results of this study will be used in a final manuscript and publication. This manuscript and any potential poster or oral presentations will contain no identifying information.

CONTACT

If you have questions at any time about the study or the procedures or experience adverse effects as a result of participating in this study you may contact the researcher, Robyn Grunberg, grun4640@mylaurier.ca.

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. You have the right to refuse to answer any question or participate in any activity you choose.

FEEDBACK & PUBLICATION

The results of this research might be published/presented in a thesis, course project report, book, journal article, conference presentation, class presentation. An executive summary of the findings from this study will be available by Spring 2020. You can request the executive summary by emailing grun4640@mylaurier.ca.

CONSENT

I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Participant's signature_____________________________________ Date __________________

Investigator's signature____________________________________

Date __________________

LIFESPAN PSYCHOMOTOR BEHAVIOUR LAB

WILFRID LAURIER UNIVERSITY
LAURIER
Inspiring Lives.

Appendix D: Waterloo Handedness Questionnaire

WATERLOO HANDEDNESS QUESTIONNAIRE

Instructions

Answer each of the following questions as best you can. If you always use one hand to perform the described activity, circle **RA** or **LA** (for right always or left always). If you usually use one hand circle **RU** or **LU** (for right usually or left usually), as appropriate. If you use both hands equally often, circle **EQ**.

Do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, then mark the appropriate answer. If necessary, stop and pantomime the activity.

1. Which hand do you use for writing?
   LA LU EQ RU RA
2. In which hand would you hold a heavy object?
   LA LU EQ RU RA
3. With which hand would you unscrew a tight jar lid?
   LA LU EQ RU RA
4. In which hand do you hold your toothbrush?
   LA LU EQ RU RA
5. With which hand would you pick up a penny off a desk? LA LU EQ RU RA
6. In which hand would you hold a match to strike it?
   LA LU EQ RU RA
7. With which hand do you throw a baseball?
   LA LU EQ RU RA
8. With which hand would you pet a cat or a dog?
   LA LU EQ RU RA
9. Which hand would you use to pick up a nut or a washer?
   LA LU EQ RU
10. Which hand do you consider the strongest? LA LU EQ RU RA
11. Over which shoulder would you swing an axe?
    LA LU EQ RU RA
12. With which hand would you pick up a comb?
    LA LU EQ RU RA
13. With which hand do you wind a stopwatch?
    LA LU EQ RU RA
14. With which hand would you pick up a bat?
    LA LU EQ RU RA
15. With which hand would you pick up a piece of paper off a desk? LA LU EQ RU RA
16. With which hand do you use a pair of tweezers?
    LA LU EQ RU RA
17. With which hand would you throw a spear?
    LA LU EQ RU RA

18. With which hand would you hold a cloth when dusting furniture? LA LU EQ RU RA
19. With which hand do you flip a coin?
    LA LU EQ RU RA
20. In which hand would you hold a knife to cut bread?
    LA LU EQ RU RA
21. With which hand do you use the eraser on the end of a pencil? LA LU EQ RU RA
22. With which hand would you pick up a toothbrush?
    LA LU EQ RU RA
23. With which hand would you hold a needle when sewing? LA LU EQ RU RA
24. On which shoulder do you rest a baseball bat when batting? LA LU EQ RU RA
25. In which hand would you carry a briefcase full of books? LA LU EQ RU RA
26. In which hand would you pick up a jar?
    LA LU EQ RU RA
27. With which hand do you hold a comb when combing your hair? LA LU EQ RU RA
28. With which hand would you pick up a pen?
    LA LU EQ RU RA
29. Which hand do you use to manipulate implements such as tools?
    LA LU EQ RU RA

30. Which hand would you use to put a nut washer on a bolt?
LA LU EQ RU RA
31. With which hand would you pick up a baseball?
LA LU EQ RU RA
32. Which hand is the most adept at picking up small objects?
LA LU EQ RU RA

33. Is there any reason (ie. injury) why you do not use the hand you prefer to use for any of the above activities?
YES NO (Circle one)
If yes, please explain why you do not use your preferred hand and which activities are affected.

34. Have you ever been given special training or encouragement to use a particular hand for certain activities?

YES NO (Circle one)
If yes, please explain the special training and which activities are affected.

Appendix E: Participant Demographics

Age	Sex	WHQ Score	Specific Training
25	M	32	N/A
26	M	22	Tool training (flooring)
24	F	21	N/A
23	F	30	Basketball (R hand)
23	F	30	N/A
23	F	31	N/A
23	M	30	N/A
21	F	32	Volleyball (R hand)
19	F	26	Sport training (L hand)
22	F	28	In kindergarten, she was trained to use R hand over L by teacher
24	M	16	N/A
30	F	29	N/A
23	F	29	N/A
18	F	31	N/A
22	F	17	N/A
22	F	31	N/A
22	F	32	N/A
23	M	32	N/A
25	M	27	N/A
24	F	30	Piano
21	M	16	N/A
25	M	30	N/A
21	F	30	N/A
24	M	31	N/A
30	M	32	N/A
22	F	26	N/A

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