The Contribution of Visual & Somatosensory Input to Target Localization During the Performance of a Precision Grasping & Placement Task

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Kinesiology

Waterloo, Ontario, Canada, 2017

Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Objective: Binocular vision provides the most accurate and precise depth information; however, many people have impairments in binocular visual function. It is currently unknown whether depth information from another modality can improve depth perception during action planning and execution. Therefore, the goal of this thesis was to assess whether somatosensory input improves target localization during the performance of a precision placement task. It was hypothesized that somatosensory input regarding target location will improve task performance.

Methods: Thirty visually normal participants performed a bead-threading task with their right hand during binocular and monocular viewing. Upper limb kinematics and eye movements were recorded using the Optotrak and EyeLink 2 while participants picked up the beads and placed them on a vertical needle. In study 1, somatosensory and visual feedback provided input about needle location (i.e., participants could see their left hand holding the needle). In study 2, only somatosensory feedback was provided (i.e., view of the left hand holding the needle was blocked, and practice trials were standardized). The main outcome variables that were examined were placement time, peak acceleration, and mean position and variability of the limb along the trajectory. A repeated analysis of variance with 2 factors, Viewing Condition (binocular/left eye monocular/right eye monocular) and Modality (vision/somatosensory) was used to test the hypothesis.

Results: Results from study 1 were in accordance with our hypothesis, showing a significant interaction between viewing condition and modality for placement time ($p=0.0222$). Specifically, when somatosensory feedback was provided, placement time was >150 ms shorter in both monocular viewing conditions compared to the vision only condition. In contrast, somatosensory feedback did not significantly affect placement time during binocular viewing. There was no evidence to support that motor planning was improved when somatosensory input about end target location was provided. Limb trajectory showed a deviation toward needle location along azimuth at various kinematic markers during movement execution when somatosensory feedback was provided. Results from study 2 showed a main effect of modality for placement time ($p=0.0288$); however, the interaction between modality and vision was not significant. The results also showed that somatosensory input was associated with faster movement times and higher peak accelerations. Similar to study one, limb trajectory showed a deviation toward needle location at various kinematic markers during movement execution when somatosensory feedback was provided.

Conclusions: This study demonstrated that information from another modality can improve planning and execution of reaching movements under certain conditions. It may be that the role of somatosensory input is not as effective when practice is not administered. It is important to note that despite the improved performance when somatosensory input was provided, performance did not reach the same level as was found during binocular viewing. These findings provide new knowledge about multisensory integration during the performance of a high precision manual task, and this information can be useful when designing new training regimens

for people with abnormal binocular vision.

Acknowledgements

This research was supported by funding from the Banting Research Foundation, and the Senate Graduate Scholarship funding from the University of Waterloo.

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Section 1: General Introduction

The main benefit of having two functionally normal eyes is the ability to see in depth. Having the ability to perceive the location of a target object is a critical requirement for everyday goal-directed movements. The performance of fine motor skills, such as reaching and grasping, is disrupted when visual function is reduced in one eye (Melmoth, Storoni, Todd, Finlay, & Grant, 2007; Piano & Connor, 2013). More specifically, prehension movements are slower, and deficits are more pronounced in the final approach phase of a reaching and grasping movement (Melmoth et al., 2007). The impairment in binocular function may also affect other important functions, for example, educational performance, social interactions, and overall quality of life (Chua & Mitchell, 2004; Connor, Birch, Anderson, & Draper, 2010; Packwood, Cruz, Rychwalski, & Keech, 1999; Rahi, Cumberlan & Peckham, 2006; Webber, Wood, Gole, & Brown, 2008). Abnormal binocular vision currently affects more than 44% of older adults over the age of 60 and 2-3% of otherwise normally developing children within the population (American Academy of Ophthalmology, 2013). Thus, investigating the contribution of binocular vision to the performance of goal-directed movements is a critical starting point towards developing potential training regimens for those with impaired binocular function.

Sensory information provided by each modality is used at various processing stages of goal-directed movements, including target localization, motor planning, and movement execution. To locate a target object within the environment, sensory input must be provided from one or more sensory modalities, such as the visual and somatosensory systems. The visual system provides information about the object’s features such as texture, size and orientation, its 3-dimensional (3D) location, as well as information about the surrounding environment and the position of the limb. The visual system uses many monocular (e.g., relative, size, texture, motion parallax, accommodation) and binocular cues (ocular vergence and binocular disparity) to localize objects in 3D space (Howard & Rogers, 2002). Although both binocular and monocular viewing provide depth cues, previous studies have shown a greater decrement in prehension occurs when binocular vision is removed or degraded (Jackson, Newport, & Shaw, 2002; Loftus, Servos, Goodale, & Mon-Williams, 2004; Melmoth et al., 2007; Piano & Connor, 2013; Tresilian, Mon-Williams, & Kelly, 1999). Specifically, studies have shown that ocular vergence provides reliable input about the object’s 3D location which is important for planning the reaching movement (Dijkerman, 1999; Brenner & Van Damme, 1998; Tresilian et al, 1999), whereas stereopsis provides the most precise information about object’s features which is important for planning the grasping movement (see Levi et al 2015 for review). Therefore, the performance of upper limb goal-directed movements are faster, more accurate and precise during binocular viewing compared to monocular viewing.

According to the Woodworth's model (1899), the control of reaching movements consists of two phases: the initial impulse phase and the current control phase. The initial impulse involves ballistic control to bring the limb towards the target, whereas the current control phase uses sensory feedback to reduce any discrepancy between the limb and target location. Woodworth’s model was refined recently by Elliott and colleagues (2010). The multiple-processes model of limb control proposed that during movement execution, two online control mechanisms are activated: early online control and late online control. These online control processes are centered around a concept known as the internal model, which is a simulation of the sensory-motor transformation for a given motor behavior (Sabes, 2000; Shadmehr, Smith, &

Krakauer, 2010; Wolpert, 2007). Early online control is based on the activation of the internal model, which uses the efference copy to simulate the movement and predict an outcome. If a discrepancy is detected between the desired and the simulated outcome, adjustments to the movement trajectory can be potentially initiated even before sensory information is acquired and processed. Late online control compares sensory feedback (reafference and exafference) with the expected sensory consequences. In order to engage in the early online control processes, the internal model must be accurate and precisely calibrated, so that predictions of the upcoming movements are accurate. The accuracy of the internal model for motor control depends on the accuracy and reliability of the input provided by each sensory system. The reliability of input can vary across each modality and also within a modality. For example, the reliability of depth cues varies during binocular and monocular viewing. Because depth perception and object localization seem to be less accurate and precise during monocular viewing, it is important to examine whether another modality could provide a useful source of input for the planning and execution of goal-directed movements.

Another modality that can provide reliable information about 3D target location when the limb is in contact with a target object is the somatosensory system. The proprioceptive cues within the somatosensory system come from muscle spindles and Golgi tendon organs which provide input regarding the orientation and motion of body segments (Kandel, Schwartz & Jessell, 2000; Sarlegna & Sainburg., 2009). Previous studies have shown that proprioceptive information is critical for movement planning (Larish et al., 1984) and movement execution, as the input helps to update the initial motor plan (Sainburg, Ghilardi, Poizner, & Ghez, 1995). Additonal research has shown that adults integrate visual and somatosensory inputs optimally during the performance of both perceptual and/or motor tasks (Ernst & Banks, 2002; van Beers, Sittig, & Gon, 1999). Through the process of multisensory integration, the central nervous system (CNS) can combine the redundant information from each modality in order to achieve a more accurate and precise representation of the environment. Therefore, somatosensory input about target's location during monocular viewing may enhance the ability to localize a target object; however, no research to date has been conducted to address this question. Thus, the conceptual framework, illustrated in Figure 1.1, was developed to guide this thesis and answer the following question: Does somatosensory information specifying target's 3D location improve to movement planning and execution during monocular viewing?

The integration of sensory inputs from multiple senses provides important behavioural benefits during the performance of various perceptual and motor tasks in healthy adults (Ernst & Banks, 2002, van Beers et al., 1999). Understanding the contribution of different modalities during movement planning and execution will provide new knowledge that can be useful when developing more effective training programs for people with abnormal binocular vision. The following literature review will comprehensively examine the current state of knowledge about the contribution of the visual and somatosensory systems during the planning and execution of movements, and their role in the performance of goal directed upper limb movements.

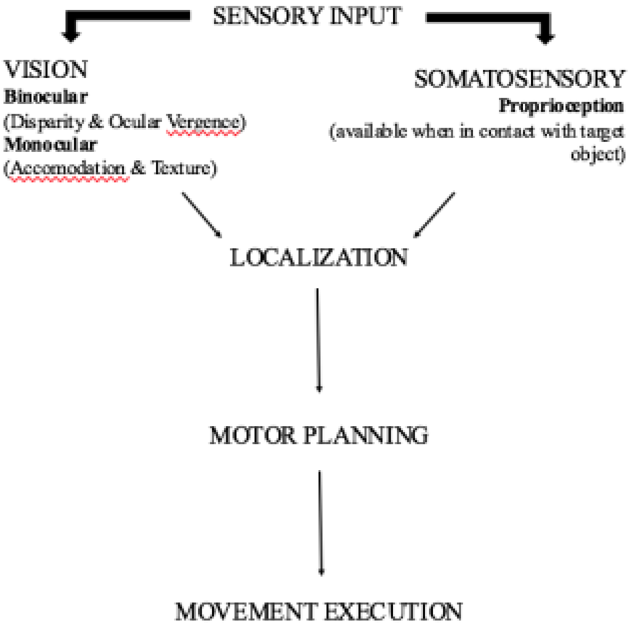


Figure 1.1: Framework for integration of visual and somatosensory input during the performance of goal directed movements.

Section 2: Literature Review

2.1 Modality Specific Cues that Contribute to Localization

An accurate representation of a target location (distance and direction) is needed prior to the planning and execution of goal-directed movements. Input about the location of an object can be provided through the visual and somatosensory modalities, if the target is in contact with the body. Within each modality there are specific cues that contribute towards distinguishing the absolute (egocentric) distance and direction of the target with regards to one's self, yet some of these cues may be more accurate and reliable than others. Thus, understanding the contribution of the visual and somatosensory modalities to target localization is important because of its potential affect towards motor planning and movement execution.

2.1.1 The Visual Systems Contribution through Binocular and Monocular Cues

Vision provides important sensory information that contributes to the performance of upper limb movements, such as reaching and grasping (Elliott, Helsen & Chua, 2001; Elliott et al., 2010; Goodale & Westwood, 2004; Howard, 2012; Jeannerod, Arbib & Rizzolatti, 1995). When planning a reaching movement, vision provides input specifying the extrinsic properties of an object, such as the distance and orientation of the target object (Watt & Bradshaw, 2000). On the other hand, the grasping phase requires intrinsic visual input about the object, which specifies its size, shape and texture (Watt & Bradshaw, 2000).

Two binocular cues that contribute to encoding of intrinsic and extrinsic object properties are stereopsis and ocular vergence. Stereopsis, arising from horizontal retinal disparities, is a sensory cue that provides depth information to accurately judge an object's orientation, relative size and distance in the near environment (McKee & Taylor, 2010). Ocular vergence involves horizontal, disjunctive eye movements (convergence/divergence) which are initiated to reduce binocular disparity (Howard & Rogers, 1995; Tondel & Candy, 2007). Although both stereopsis and ocular vergence provide relative depth information, absolute depth can only be acquired through the cue of vergence. During vergence eye movements, input in the form of motor efference, or proprioception from the extraocular eye muscles (lateral and medial recti muscles) informs the brain of where the eyes are in the orbit (Howard & Rogers 2002). Thus, the muscular effort associated with vergence movement provides information about the position of the eyes in orbit, and absolute depth can be inferred based on this input. In summary, horizontal stereopsis only allows for relative depth information, whereas 3D object location is needed to plan a reaching movement, which requires absolute depth information that can be obtained from ocular vergence.

The role of ocular vergence in depth perception has been previously examined during a prehension task (Mon Williams & Dijkerman, 1999). Ocular vergence was manipulated using horizontal prisms to change the perceived target distance. Base in and base out prisms distort the perceived direction and distance of the target by shifting the image on the retina either nasally, or temporally. The eyes then move to realign the image on the retina to reduce disparity. A disruption by the prisms causes the target object to appear farther (base-in), or closer (base-out) than the actual target distance, which in turn affects the kinematic measures during a reaching and grasping movements. For example, Mon William and colleagues (1999) reported that peak velocity and acceleration were lower, and the deceleration phase was longer when subjects wore base-out prisms. On the other hand, higher peak velocities and accelerations as well as shorter deceleration phases where shown when base-in prism were worn (Mon Williams et al., 1999). Thus, ocular vergence plays an important role in perceiving the location of the target in depth which directly affects the planning of prehension movements. Although this study provided input about the role of ocular vergence, it did not examine the precision of this cue. To further add to the literature, Tresilian and colleagues (1999), determined that the precision of vergence is dependent on distance. More specifically, if the target falls outside of the 2-3m range, then convergence/divergence ability is limited. Thus, this cue becomes unreliable in perceiving target distance beyond 2 metres.

During monocular viewing, the ocular vergence signal is disrupted due to the phoria. (Ono & Weber 1981). Phoria occurs when the covered eye deviates outward (exophoria), or inward (esphoria). Previous studies have shown that phoria disrupts judgements of visual direction, which is associated with mislocalization of the target object along the azimuth (Ono & Gonda 1978; Ono & Weber 1981; Hrynchak, Herriot, & Irving, 2010; Mapp, Ono, & Khokhotva, 2007). For example, a temporal eye deviation of the right eye (exophoria) will result in reduced vergence angle (i.e., increased divergence). This means that the target will be mislocalized along the azimuth and depth, which causes the individual to perceive the target location farther to the left and farther in depth than the actual physical target location. In the case of esophoria, the eye deviates inward and the target appears shifted toward the seeing eye (Mapp et al., 2007). If the right eye is again occluded, the target will be perceived to the left of where the object is actually located. To summarize, ocular vergence does not provide a reliable depth cue during monocular viewing because phoria (in covered eye) leads to localization errors along the azimuth and depth.

Target localization during monocular viewing can be achieved using other depth cues.

For example, pictorial cues such as relative size, texture, and height in the visual field, motion cues, such as motion parallax during lateral head movement, and ocular cue, such as accommodation, all provide some depth information (Granrud, Yonas, & Opland, 1985; Oshea, Blackburn, & Ono, 1994; Yonas & Granrud, 2006). However, the majority of studies that examined the performance of prehension movement have shown that the execution of these movements is slower, less accurate and precise when binocular vision is not available (Servos et al., 1992; Servos & Goodale, 1994). Therefore, the monocular depth cues are not as reliable when planning and executing upper limb reaching and grasping movements.

2.1.2 The Somatosensory Systems Contribution through the Proprioceptive Cue

Another modality that provides intrinsic and extrinsic information regarding a target object is the somatosensory system. Within the somatosensory system is the proprioceptive cue, which is most important for providing information about the relative position of body segments. There are two types of proprioceptors found in skeletal muscles; Golgi tendon organs and muscle spindles. Golgi tendon organs (GTO) are located between the muscle fibres and tendon. GTOs main function is to signal changes in muscle tension to provide precise information about the state of the contracting muscle (Kandel, Schwartz & Jessell, 2000). On the other hand, muscle spindles are located in the muscle belly, and detect changes in muscle length. These changes in the length of muscles are associated with a change in the angles of joints that the muscles cross (Kandel, Schwartz & Jessell, 2000), and can provide the CNS with information about the location of body segments. Therefore, when the limb is in contact with the target object, information regarding target's location can be obtained.

The ability to localize a target using the somatosensory system is dependent on the precision of the proprioceptive input. A study by van Beers and colleagues (1998) examined the precision of proprioceptive input in localizing one's own unseen hand. Participants were instructed to complete a position-matching task under three conditions: visual target matching with the unseen left hand (VL), visual target matching with the unseen right hand (VR), and matching the unseen right hand on the table top with the left hand on the bottom side of the table (RL). Proprioceptive localization was determined by comparing the spatial distribution during the visual and proprioceptive conditions. The results showed that proprioceptive localization (RL) was more precise in the radial direction with respect to the shoulder and more precise when the hand position was closer to the shoulder than further away. More specifically this study found that proprioceptive localization of the elbow and shoulder angles had a precision of roughly 0.6±1.1 degrees, which corresponds to previously examined values of 0.5-0.7 degrees (Scott & Loeb, 1994) obtained from experimental paradigms that involved matching the limb/fingertip position (McCloskey, 1973). In addition, it is important to remember that other factors can affect the proprioceptive position sense, such as, active versus passive placement of the limb (Paillard & Brouchon, 1968), starting position of the limb (Craske & Crawshaw, 1974) and the speed of limb during movement (Clark & Horch, 1986). In summary, research clearly shows that input from the somatosensory system provides reliable input about the position of the limb. Next, it is important to consider how inputs from each modality are integrated during localization tasks.

2.1.3 Localization Using Both Visual and Somatosensory Inputs

In previous years' researchers have studied each modality in isolation, yet within the last 10 years interest in multisensory integration has risen exponentially (Van der Stoep, Nijboer, Van der Stigchel, & Spence, 2015). Through the process of multisensory integration, the CNS can combine redundant sensory information in order to achieve a more accurate and precise representation of the object, or the environment. For instance, the ability to integrate information from the visual and somatosensory systems contributes to everyday visually guided goal-directed movements, such as reaching and grasping. However, how the input from these modalities is combined during the planning and execution of goal-directed movements remains to be fully established (Sarlegna & Sainburg, 2009).

Multisensory integration has been studied during localization tasks. For example, Van Beers and colleagues (1999) examined localization using input from the visual and somatosensory modalities. This study involved participants matching the position of the unseen left hand under three different conditions: proprioceptive (P) input only, vision (V) only condition and vision and proprioception (PV). In the proprioceptive condition participants were instructed to match the unseen right hand on the table-top with the unseen hand on the underside of the table top. In the vision condition the unseen left hand on the underside of the table was matched to a visual target. During the vision and proprioceptive condition, subjects were able to see the right hand while trying to match its position using the unseen left hand. Findings showed that proprioceptive localization is more precise in the radial direction with respect to the shoulder, and visual localization is more precise in the azimuthal direction with respect to the cyclopean eye (van Beers et al., 1998,1999). Furthermore, this study showed a direction-dependent weighting of the proprioceptive and visual information; the weighting being related to the precision of the unimodal information in each direction (van Beers et al., 1999).

Additional research suggests that vision is important for determining reach direction while proprioception is critical for reach amplitude (Cameron & López-moliner, 2015; Monaco et al., 2010). A study by Monaco and colleagues examined reaching towards visual and body-defined targets, with a main focus on reach endpoint accuracy and precision. Their methods varied from that of van Beers and colleagues (1996, 1998, 1999) as they manipulated target modality and visual feedback. Participants were asked to reach towards targets that were located in their peripheral vision; therefore, it was not surprising that accuracy was reduced in the vision condition. In the second experiment participants were asked to make a reach towards a visual target or bodily target (left index finger) while visual feedback about the target was manipulated: preview and full vision during the reach, preview and brief vision (100ms of the reach), and preview only (no visual feedback during the reach). Their findings showed that endpoint variability was lower for amplitude (y-axis) when the target was presented proprioceptively compared to visually. Cameron and colleagues (2015) showed similar findings to that of Monaco and colleagues (2010), however their study focused on the online characteristics of the reaching movement. To summarize, results from these studies suggest that the proprioceptive modality plays a role in regulating movement amplitude, whereas the input from the visual modality is important in reducing directional error along the azimuth.

2.2 Phases of Goal-Directed Movement

A major function of each modality is to provide input to plan and execute goal-directed movements. The brain integrates information from each sensory system through a process known as sensorimotor transformation. Sensorimotor processing is thought to occur in three stages: sensory stage (object detection, identification and localization), motor planning, and movement execution (Desmurget, Pélisson, Rossetti, & Prablanc, 1998). For example, sensory input specifying object location is combined with the sensory input regarding the initial location of the effector to compute the appropriate movement vector. Depending on the modality that specifies target location, the sensory input is then transformed into an appropriate frame of reference for a given movement. For example, eye movements are planned and executed in a gaze-centered coordinate frame, whereas arm movements are programmed in a shoulder-centered coordinate frame (Desmurget et al., 1998). Thus, when reaching towards a visual target, sensory information about the initial target position must be transformed into the appropriate frame of reference required for planning the movement.

If an error in motor planning occurs due to reduced reliability of sensory cues, or a perturbation occurs, the ongoing movement can be corrected during execution, which has been referred to as online control (Elliott et al., 2010). As proposed by the multiple processes model of limb control, the early online control is dependent on the efference copy of the motor command along with the predicted outcome, which can be used to detect a discrepancy between the desired and the simulated outcome. If an error is detected, adjustments to the movement trajectory can be potentially initiated before sensory information is processed. Late online control depends on sensory feedback (reafference and exafference), which can be compared the expected sensory consequences. Both, early and late online control processes ensure that movements are executed with minimal errors. In summary, accurate and reliable sensory input is required for each phase of goal-directed movements: localization, motor planning, and execution. The relative contribution of each modality might differ during the three phases, which could be dependent on the reliability of the sensory input, and the type of action.

2.2.1 The Role of the Visual System During Movement Planning and Execution

For visually-normal people, vision is the predominate modality used for target localization during everyday tasks. After a target is localized, a motor plan must be computed before the movement is initiated (Sarlegna & Sainburg 2009). Studies have shown that end-point error is reduced when vision of the initial arm position is available during motor planning (Desmurget et al. 1998, Elliott et al. 1991; Ghez, Gordon, Ghilardi & Sainburg, 1995; Prablanc, Echallier, Komilis & Jeannerod, 1979b). Visual feedback during movement execution is also used for online control. This is supported by studies which showed that the reach deceleration phase is longer, and the endpoint variability is reduced when vision is available during movement execution (Saunders & Knill., 2003; Khan et al., 2006, Elliott et al., 2010). Therefore, vision provides important sensory input during the performance of upper limb movements.

One important aspect of vision is the fact that visual information is acquired with two eyes, that is, binocularly. The contribution of binocular vision to the performance of reaching and prehension movements has been investigated extensively (Servos et al., 1992; Servos & Goodale, 1994; Bingham & Pagano 1998; Loftus et al., 2004; Mon-Williams & Dijkerman 1999). (Loftus et al., 2004)The first study on this topic, conducted by Servos and colleagues (1992), instructed subjects to make quick, accurate, and natural reaches towards a block and then grasp it using the thumb and index finger during two viewing conditions (binocular, monocular). Results showed that during a monocular viewing condition subjects had slower movement initiation and spent a greater amount of time in the deceleration phase when compared to binocular viewing condition. Furthermore, reach peak velocity and acceleration were reduced during monocular compared to binocular viewing. This may indicate that subjects moved more cautiously and engaged in more online control processes during monocular viewing since most modifications occurred during the low velocity phase of the movement (Servos et al., 1992). In summary, results from many studies suggest that binocular vision provides more accurate information about target's location and its features, which leads to a more accurate motor plan and more efficient online control.

Most experiments that examined the role of binocular vision in the performance of prehension used an eye patch to cover one eye, which not only removed binocular cues but also reduced the field of view. In order to provide a better insight into the role of binocular cues Bradshaw and colleagues (2004) investigated a reaching and grasping using a task that was performed under binocular (two different views present to each eye), bi-ocular (two identical views present to each eye, i.e., no stereopsis) and monocular (one eye only) viewing conditions. The findings showed that peak velocity was higher and peak grip apertures were smaller during binocular viewing in comparison to monocular and bi-ocular viewing conditions. Although peak-velocity is only an indirect measure of perceived distance, other measures showed similar results. The number of corrections (under reached) and collisions (over-reached) between monocular and bi-ocular viewing showed no significant difference, however, both of these conditions differed significantly from binocular viewing. These results indicate that monocular and bi-ocular cues do not provide adequate depth information and therefore result in more reaching errors during movement.

Overall, it is evident that performance is affected under monocular viewing conditions, thus raising question as to whether another modality can help provide additional sensory input towards improving target localization, planning and execution of goal-directed movements.

2.2.2 The Role of the Somatosensory System During Movement Planning and Execution

The somatosensory system contains the proprioceptive cue which provides input regarding the orientation and motion of body segments. As previously stated, this input can be used to locate an object when the limb is in contact with that object. It is possible that proprioceptive input regarding object's location could help to plan and execute movements. Having input about the end location of the movement can potentially provide advantages for movement planning and also help to reduce errors in movement execution. Therefore, investigating the contribution of proprioceptive input to motor planning and movement execution is critical in determining whether this modality can be used to enhance the performance of goal-directed actions.

One way of determining the contribution of somatosensory input is through tendon vibration. A study by Larish and colleauges (1984) showed that in the absence of visual feedback, limb vibration prior to movement alters the final position of the limb. More specifically, the muscle vibration affected the perception arm position as being displaced. This displacement caused an error in the movement vector due to initial limb position being incorrectly determined (DiZio et al. 1993; Lackner and Taublieb 1984; Larish et al. 1984). This study indicates that proprioceptive input may be critical in providing information for the initial configuration of movement planning. Similarly, additional research examined the role of proprioceptive input during online correction of reaching movements to perturbed targets when no vision of the hand was provided (Prablanc & Martin, 1992; Prablanc, Pelisson, & Goodale, 1986; Bagesteiro, Sarlegna & Sainburg, 2006; Sarlegna et al., 2003). In a more recent study, the contribution of proprioceptive input was examined in a more complex movement compared to pointing tasks (Gosselin-Kessiby, Messier, & Kalaska, 2008). This study used a task requiring participants to insert a letter into slots that contained various orientations. The findings showed that participants changed the orientation of the letter in order to match the slot, even when the instructions stated that the orientation of the letter at the start of reach had to be maintained. This automatic online correction occurred even when participants had only proprioceptive information about both the angle of the slot and the angle of the letter.

To summarize, somatosensory input is essential for optimal performance of goal-directed upper limb movements. More specifically, somatosensory input specifies the initial limb position during movement planning, and it can be used for online corrections during movement execution. Although having proprioceptive input in isolation helps to determine its role in movement execution, it is important to consider how proprioception contributes to movement planning and execution when input is also provided from the visual modality.

2.3 Multisensory Integration During the Performance Goal-Directed Movements

Multisensory integration is important for human perception and action. For instance, the ability to integrate information from two modalities, like the visual and somatosensory systems, can help during the performance of everyday goal-directed movements. The input from multiple systems allows for a more precise representation of the target object, which facilitates planning and execution of movements. The input from more than one system can also be beneficial when one modality is unable to provide accurate information about the object's features and its location.

Within the past decade researchers have tried to determine how the brain integrates three-dimensional information about the world from different sensory cues (Ernst & Banks, 2002; Knill & Saunders, 2003; Landy, Maloney, Johnston, & Young, 1995). An interpretation of experimental findings suggests that the weighting given to each modality is dependent on the relative reliability of the sensory cue. This minimum-variance model (MLE) has been used to explain the integration of vision and touch (Ernst and Banks, 2002) and other sensorimotor tasks (van Beers 1996, 1999). This model indicates that reduced variance occurs during bimodal conditions, compared to each unimodal condition in isolation.

One of first studies that assessed multisensory integration during motor task performance was conducted by Sober and Sabes (2003). The purpose of the study was to determine whether a single criterion is used to combine sensory inputs, or whether different combinations of sensory inputs are used at different stages of motor planning. Using a different model then the minimum variance model that was previously explained, the contribution of proprioception and vision inputs were examined. The velocity command model used the movement vector (MV) error, which was calculated by subtracting the estimated initial arm position from the target location (Sober et al., 2003). The transformation of the extrinsic movement vector into a joint-based (intrinsic) motor command (Ghilardi, Gordon & Ghez, 1995; Goodbody and Wolpert, 1999) is referred to as the inverse model (INV) error. The findings of this study showed that arm position estimates used for vector planning relied mostly on visual feedback, whereas the estimate used for converting desired movement vector into a motor command relied more on proprioceptive signals. Therefore, this study indicates that each modality is weighted differently at the two stages of motor planning.

To further expand on the literature of goal-directed movement, a study by Cameron and colleagues (2015) examined the contribution of visual and proprioceptive input during online control. The purpose of this study was to determine the interaction between target modality and effector vision by manipulating the way in which the target was defined: vision only, proprioception only, both vision and proprioception. Both constant error (mean endpoint relative to target location) and variable error (standard deviation of endpoints) were examined in amplitude and direction. The results showed that participants tend to reach with a shorter amplitude when no proprioceptive information about the target was provided. Therefore, this study shows that proprioceptive input contributes mainly to online correction along the depth axis (Cameron et al., 2015). This finding is similar to those of previous findings that report proprioceptive input being more reliable in depth, and vision more reliable in azimuth (Monaco et al., 2009; van Beer et al., 1998).

In conclusions, relatively few studies examined the contribution of visual and somatosensory input towards the performance of reaching and grasping movements. The proposed studies in this thesis will use a kinematic approach to examine how visual and somatosensory inputs are used during the planning and execution of a high-precision motor task, when both modalities simultaneously provide input about target location.

2.4 Rationale for the Proposed Research

Binocular vision provides an important sensory input regarding object location in 3D space, which is critical for the performance of goal-directed movements. Thus, one aspect of performance that is impaired by the absence of binocular vision is target localization in 3D space. Previous research has shown that redundant sensory information can be integrated by the CNS to reduce the uncertainty associated with unisensory cues; however, it is currently unknown whether depth information from another modality can improve object localization during action planning and execution. Therefore, the purpose of this research was to examine the role of somatosensory input in target localization during the performance of a precision grasping and placement task in adults.

The task selected to examine visuo-somatosensory integration during goal-directed movements in this research was bead threading. The performance of this task requires 3D localization of the bead and the needle, as well as precision grasping when picking up the bead, and accurate reaching to place the bead on the needle. Previous studies have shown that the bead threading task is a complex visuomotor task, which is dependent on binocular visual input because performance is significantly impaired during monocular viewing (Piano & O'Connor 2013; Alramis, Christian, Roy & Niechwiej-Szwedo, 2016; Gonzalez & Niechwiej-Szwedo, 2016). Therefore, examining the integration of visual and somatosensory input during the bead-threading task may provide unique insight towards the contribution of each modality in the planning and execution of goal-directed movements.

In our bead threading task, visual and somatosensory inputs contribute to the planning and execution of two separate components: reaching towards the needle (i.e., limb transport) and bead placement on the needle. Therefore, it is important to consider the contribution of the visual and somatosensory modalities to the control of limb trajectory during reaching and placement. To be more specific, peripheral vision and proprioceptive input from the right limb provide information about the limb's initial position and during the reaching phase, whereas central vision and proprioceptive input from the left limb provide information regarding needle's location. The potential contribution of these inputs during performance of the bead threading task is considered next.

To successfully complete the bead threading task, the CNS must obtain sensory information regarding the target's location in 3D space, which is provided through visual and somatosensory input. The visual input involves central vision because the needle is fixated, thus, the CNS can localize the targets location based on the signal from the eye muscles, indicating the vergence posture of the eyes. Proprioceptive input is provided through the left limb, which is holding the base of the needle, therefore, the CNS can localize the target based on the signals from the limb muscle proprioceptors. Previous research has shown that redundant sensory inputs are integrated optimally, which is associated with improved performance. Therefore, it was expected that having somatosensory input from the limb in direct contact with the target, in addition to the visual information, will increase the certainty in target localization, and improve motor planning of the reach component. Specifically, greater certainty in target localization would be associated with increased peak acceleration, faster movement time, and less variability in limb position during the initial part of the trajectory (i.e., the acceleration phase). Furthermore, if reach planning is more accurate and/or precise due to visuo-somatosensory integration, this could also improve the control of the limb's trajectory in the deceleration phase, for example, reduced limb trajectory variability. Finally, the additional somatosensory input may also facilitate the performance of the second component, that is, the placement task.

Peripheral vision and proprioceptive input from the moving right limb are important during the planning and execution of reaching. During motor planning and the early stages of the reach, the right limb appears in the periphery. Previous research showed that endpoint accuracy is reduced when vision of the limb is removed or altered prior to movement onset (Desmurget et al., 1998). Therefore, having peripheral vision regarding the start position of the right limb benefits reach planning. During movement execution, peripheral visual feedback can be used to make adjustments in limb trajectory (Franklin & Wolpert, 2008; Sarlegna et al., 2004; Saunders & Knill, 2004). More specifically, peripheral vision can provide important information for adjusting the direction of rapid movements (Bard, Hay, & Fleury, 1985; Blouin, Teasdale, Bard, & Fleury, 1993; Paillard, 1996; Proteau, Boivin, Linossier, & Abahnini, 2000; Sarlegna et al., 2004).

2.5 Research Objectives & Hypotheses

This thesis is designed to address the following research objectives:

Part 1: Study 1

Objective: To determine if somatosensory input specifying target location facilitates the performance of reaching and placement when the visual system provides less reliable depth cues.

Hypothesis 1: It is hypothesized that somatosensory input specifying 3D needle location will improve motor performance, such that the reaching will be executed faster and placement time will be shorter.

Hypothesis 2: It is hypothesized that somatosensory input regarding the end location will facilitate movement planning. This will be reflected in higher peak accelerations and reduced variability in limb position at this time point.

Hypothesis 3: It is hypothesized that somatosensory input will improve movement execution, as reflected by a shift of the trajectory in direction towards the needle and reduced variability in the spatial position of the limb throughout the trajectory.

Part 2: Study 2

Study 2 was designed to address two limitations that may have confounded the results and conclusions in study 1: (1) lack of standardized practice trials prior to the experimental trials could have caused greater trial-to-trial variability across the experimental trials and potential improvements in performance in the latter trials: (2) visual input of the limb providing the proprioceptive input. By seeing the limb, additional visual information regarding limb position and joint angles was available. In turn, this could have improved the precision of visual localization. In order to test whether these limitations impacted the results, study 2 added practice trials and removed vision of the limb providing feedback to examine the same objective and hypotheses as study 1.

Section 3: Study 1 - The Contribution of Visual and Somatosensory Input Regarding 3D Location to the Performance of a Precision Placement Task in Adults

3.1 Introduction

Vision provides important sensory input that contributes to the performance of most daily activities. A critical aspect of vision, known as binocular vision, involves processing inputs from both eyes to gain more accurate and precise information about object features (i.e., shape, size, orientation), and its 3D location. The ability to use both eyes leads to a binocular advantage, which is the extent to which binocular viewing results in improved performance in comparison to monocular viewing (Howard, 2002).

Binocular advantage has previously been studied during aiming, reaching and grasping movements using kinematic measures (Coull, Weir, Tremblay, Weeks, & Elliott, 2000; Gnanaseelan, Gonzalez, & Niechwiej-Szwedo, 2014; Jackson, Jones, Newport, & Pritchard, 1991; Servos et al., 1992; Melmoth & Grant, 2006; Watt & Bradshaw, 2003). These studies have shown that binocular vision provides a relatively small advantage during the execution of aiming movements towards targets presented on a computer monitor (Coull et al., 2000; Loftus, et al., 2004; Niechwiej-Szwedo et al., 2011, 2012). In contrast, binocular vision provides a significant advantage during the performance of reaching and grasping movements (Gnanaseelan et al., 2014; Melmoth & Grant, 2006; Watt & Bradshaw, 2003).

Decrements in performance, specifically for tasks that require greater precision, occur during monocular viewing. For example, several studies have shown that bead threading is a manipulation task that requires a high level of precision and is significantly dependent on binocular vision (Alramis et al., 2016; O’Connor, Birch, Anderson, & Draper, 2010; Piano & O’Connor, 2013; Webber et al., 2008). One major limitation of these studies is that they did not observe which phases of movement sequencing benefit most during binocular viewing. Because binocular vision provides more accurate and precise inputs regarding objects features (i.e., shape, size, orientation), and 3D location, it may be expected that binocular viewing impacts both, the placement and grasping. A recent study by Gonzalez and Niechwiej-Szwedo (2016) examined kinematic measures during the performance of bead-threading and found that the greatest decrement in performance during monocular viewing was evident during the placement phase. Therefore, the localization of the needle in 3D space is disrupted during monocular viewing. This raises a question as to whether another sensory system could potentially be used to localize the needle, so that performance under monocular viewing is enhanced. Although previous studies have shown improved localization when integrating input from both the visual and somatosensory modalities (Nardini, Begus, & Mareschal, 2013; van Beers et al., 1999), they did not examine how this improved performance occurs through the phases of goal-directed movement. Our study will investigate how somatosensory input is used during the motor planning and execution phases of a localization task performed under monocular viewing conditions.

The current study will incorporate the use of somatosensory feedback about the location of the needle during the performance of the bead threading task to examine if the addition of this sensory input can help with needle localization under both monocular and binocular viewing conditions. It was hypothesized that somatosensory feedback specifying needle 3D location will reduce placement time during monocular viewing in comparison to the vision only condition. This will be demonstrated through shorter placement times, and shorter movement times when reaching towards the needle. It is also hypothesized that somatosensory input will contribute to motor planning and movement execution of this task. Specifically, it was expected that with somatosensory input peak accelerations will be higher, and there will be reduced spatial variability of the limb trajectory towards the needle.

3.2 Methods

3.2.1 Participants

Fifteen students from the University of Waterloo (10 females, mean age= 22.4 ± 3.16 years), participated in the study. All subjects were right hand dominant and thirteen were right eye dominant. All participants had normal, or corrected-to-normal vision with no history of visual, or ocular abnormalities. Eye dominance was determined through eye preference when looking through a tube and by pointing to a corner of a room and closing one eye at a time. Visual acuity was assessed using vision chart, both under binocular and monocular conditions. Stereoacuity was measured using the Randot Stereoacuity Booklet (Randot SO-002 test) where subjects had to achieve at least 40 seconds of arc at a distance of 16 inches.

3.2.2 Materials and Procedure

At the initiation of each trial, participants were asked to place their index and thumb at the tip of the needle, and to close their eyes. Once the participant's eyes were closed the researcher placed the beads onto the two central hooks of the bead-board (as shown in Figure 3.1). Participants were instructed to open their eyes and fixate at the tip of the needle, then on the "go" signal, reach and grasp one bead at-a-time, and place it on the needle as fast as possible without dropping the beads. Participants were instructed to reach for the bottom bead first, and then to reach for the top bead. The task was repeated under three viewing conditions: both eyes; right-eye viewing; left-eye viewing, which were presented in a blocked fashion that was counterbalanced between participants. There were ten trials for each viewing condition. The task also involved somatosensory feedback during five of the ten trials per condition. During the somatosensory feedback trials, the participants had their left thumb and index finger placed on the needle in a standardized position, 3.5 cm from the bottom of the needle. This position was also labeled on the needle to ensure that each participant held the needle at the same location. Trials with somatosensory feedback were randomized in each of the three viewing conditions.

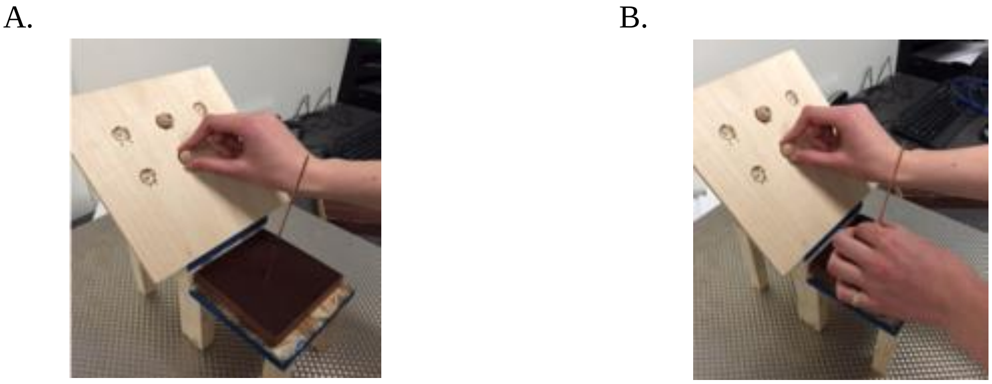


Figure 3.1: Experimental set-up illustrating the location of the bead-board and the vertical needle as well as start position of right hand during vision only (A) and somatosensory (B) modality conditions.

A board consisting of two hooks was positioned on the top tier of a two tier apparatus. The hooks were placed in two rows, which were 6 cm apart from one another along the vertical direction. Placed on the two central hooks in each row were 1.6cm diameter beads with holes that were 0.48cm wide. In line with the two central beads was a vertical needle (16.2cm long and 0.2cm in diameter) that was placed on the bottom tier of the apparatus. The distance from the chin rest to the needle was half the participant's arm length, in order to ensure comfortable reaching distance (Mean Arm Length= 69.81cm, SD=4.15cm).

Using an Optotrak 3D investigator motion capture system (Northern Digital, Waterloo, Canada), participant's upper limb kinematics were recorded. Two infrared emitting diodes (Ireds) were placed on the proximal base of the thumb and index finger. Although both fingers were recorded only the index finger was used for analysis. Grip aperture was not a measured in for this study because the Ireds were not placed at the tip of the fingers as this could potentially interfere with the participants grasping behavior. Eye movements were recorded using a head-mounted binocular eyetracker (Eyelink II, SR Research, Mississauga, Canada). Calibration for the eye tracker was performed under binocular viewing using a standard 9-point grid. Validation was performed to ensure the reliability of the calibration was <1° error. The calibration targets for eyetracker calibration were presented on a 19-inch CRT monitor (Viewsonic P95f+, 1024x768) at a viewing distance of 80 cm. Eye movement recordings were done under binocular and monocular viewing. Monocular viewing was accomplished using an infrared long-pass filter, which blocked vision in one eye but allowed a recording of the position of the covered eye. Both limb and eye movement recordings were sampled at a rate of 250Hz (Optotrak: spatial accuracy 0.4 mm, resolution 0.01 mm; Eyelink: spatial accuracy 0.5; RMS resolution 0.01°). MotionMonitor software (Innovative Sports Technology, Chicago, USA) was used to synchronize the recordings from the Eyelink II and Optotrak, and to integrate the position data into a common 3D reference frame. The Optotrak system was calibrated using a three-marker digitizing probe. The Cartesian coordinate system for Optotrak was defined by an origin located at the bottom left corner of the workspace (to the left of the apparatus). The three-dimensional system was defined with respect to the observer: horizontal plane (azimuth) as the x-axis; vertical plane (elevation) as the y-axis; median plane (depth) as the z-axis.

3.2.3 Data Reduction

3.2.3.1 Eye Position Data Reduction

One subject was excluded due to unreadable eye tracking data. Any trials where the bead was dropped were also excluded from the analysis (appendix A1). Eye position traces were examined using a customized Matlab R13 script (Matlab, Mathworks, Natick, USA) to determine how long each participant fixated at each target (bead versus needle). Fixation on the target was determined using a velocity criterion, that is, fixation on the target was defined as stable when eye velocity was <20 deg/s.

The mean vergence angle at the needle was calculated by subtracting the right eye from the left eye. The vergence angle obtained for each participant was used to calculate the vergence specified distance (VSD) for fixation on the needle. VSD was calculated for each subject using their individual interpupillary distance (IPD) (i.e., VSD = IPD / tan [vergence angle], where vergence angle = left eye position- right eye position) (Howard and Rogers 2002).

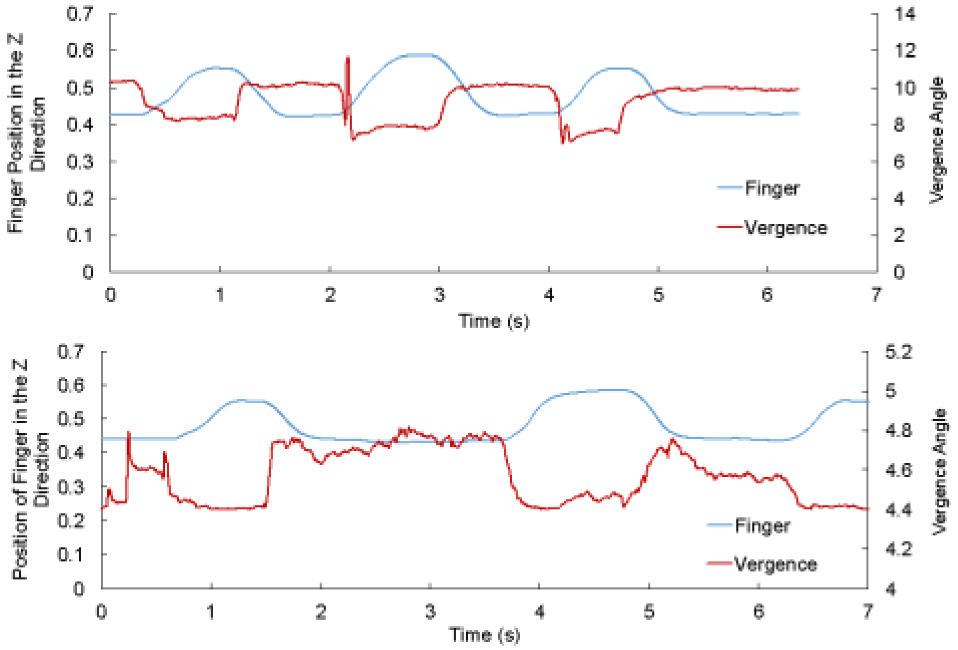


Figure 3.2: Typical trajectory of finger position in the z direction plotted with vergence eye movements during (A) binocular and monocular (B) viewing.

3.2.3.2 Optotrak Data Reduction

Five percent of trials (appendix A2) were excluded from the analysis as only successful trials, where no beads were dropped or no loss of finger tracking, were included in the kinematic analysis. Using a customized Matlab R13 script (Matlab, Mathworks, Natick, USA), the hand kinematic data were filtered using a dual-pass Butterworth filter with a low cut-off frequency of 20 Hz. The instantaneous velocities were calculated using adjacent points in the position data, and instantaneous accelerations were calculated using adjacent points in the velocity data. Velocity was used to determine the start and end of each movement towards the bead and the needle. By using velocity, we were able to define four distinct phases of the movement: 1) movement approach towards the bead (high velocity reach-to-bead phase); 2) fine adjustment and grasping phase (low velocity grasping phase); 3) movement towards the needle (high velocity reach-to-needle phase); 4) placement time (low velocity placement phase).

For the purpose of our study, we will be focusing on only two phases: transport towards the needle and placement time. The start of the transport phase to the needle was defined as when velocity reached at least 20mm/s for 20 consecutive milliseconds in the direction of the needle, with the end of the movement defined as velocity falling under 100mm/s for 20 consecutive milliseconds after peak velocity. These criterion values are consistent with previous aiming literature (Elliott, Binsted, & Heath, 1999; Elliott et al., 2010; Elliott, Hansen, & Grierson, 2009; Gnanaseelan et al., 2014; Grierson & Elliott, 2009).

Kinematic outcome measures (i.e., PV, PA, PD) were calculated using data obtained in the primary axis of the reaching movement (i.e., the z-axis). The main movement kinematic performance measures to test our first hypothesis were: movement time and placement time. The kinematic outcome measures used to test our second hypothesis were peak acceleration, mean limb position and variability in limb position at peak acceleration. Peak acceleration was defined as the maximum value obtained from the acceleration data that fell between movement start and the time of peak velocity. The following kinematic measures were used to test our third hypothesis: peak velocity (PV), peak deceleration (PD), and the mean position and variability of the limb PV, PD, and at the End of the reach. Peak deceleration value was defined as the minimum value obtained from the acceleration data that fell between the peak velocity time and movement end. Rather than restricting kinematic analysis to four distant points (PA, PV, PD, End), spatial variability was examined at additional time points within the trajectory. Specifically, the position of the limb at 50ms and 100ms intervals preceding and following PV were examined to provide a better understanding of online control throughout the movement. The mean limb position and the spatial variability of the limb throughout the reaching movement was analyzed in the azimuth (x) and depth (z) direction.

3.2.4 Statistical Analysis

3.2.4.1 Eye Position Analysis

The mean fixation duration in each viewing condition (binocular, monocular left eye, right eye) was calculated for both modality conditions (vision only, somatosensory) for all participants.

All data were approximately normally distributed, which was confirmed by examining outliers through skewness and kurtosis (appendix A3), and through a visual approach, that is, stem and leaf plots and qq plots. Mean maximum fixation duration and the associated mean vergence angle were examined using a repeated measures Analysis of Variance (ANOVA) with 2 within-subject factors: Modality (somatosensory, vision only) and Viewing Conditions (binocular, monocular left, monocular right). A post hoc Tukey test was done to determine were significance lies between means. All outcome measures are reported using means and standard errors.

3.2.4.2 Optotrak Data Analysis

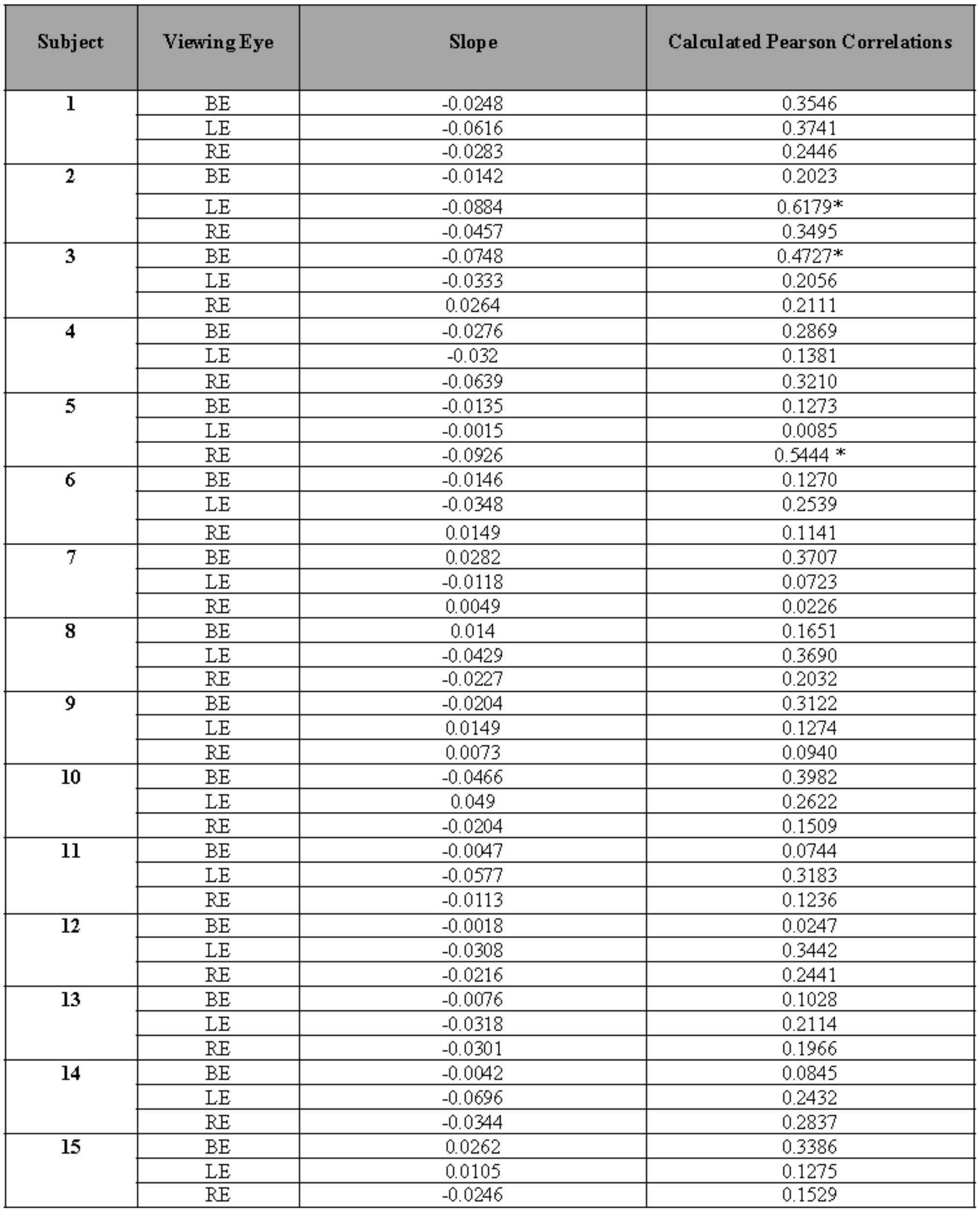
All data were approximately normally distributed which was confirmed using a visual approach, that is, stem and leaf plots and qq plots. All dependent measures were submitted to repeated measures Analysis of Variance (ANOVA) with 2 within-subject factors: Modality (somatosensory, vision only) and Viewing Conditions (binocular, left eye, right eye). A post hoc Tukey test was done to determine were significance lies between means. All outcome measures are reported using means and standard errors.

3.3 Results

3.3.1 Effects of Practice

A highly skilled task such as bead threading poses a potential limitation of practice effects from the first to last trial. In order to address the effect of practice, the placement time for trials one to ten was plotted for all fifteen subjects (appendix B). The slope and Pearson’s correlation values were examined for each participant and viewing condition to determine whether an improvement in task performance was statistically significant. In order to reach statistical significant (df=19 and $p<0.05$), a Pearson's r value of 0.433 needed to be reached. Results from the correlation analysis are shown in Table 3.1 Statistically significant improvement was found in three cases, once in each viewing condition (one binocular, left and right monocular) (Table 3.1).

Table 3.1: Pearson correlation and slope values for each participant during binocular and monocular viewing conditions.



Subject	Viewing Eye	Slope	Calculated Pearson Correlations
1	BE	-0.0248	0.3546
	LE	-0.0616	0.3741
	RE	-0.0283	0.2446
2	BE	-0.0142	0.2023
	LE	-0.0884	0.6179*
	RE	-0.0457	0.3495
3	BE	-0.0748	0.4727*
	LE	-0.0333	0.2056
	RE	0.0264	0.2111
4	BE	-0.0276	0.2869
	LE	-0.032	0.1381
	RE	-0.0639	0.3210
5	BE	-0.0135	0.1273
	LE	-0.0015	0.0085
	RE	-0.0926	0.5444 *
6	BE	-0.0146	0.1270
	LE	-0.0348	0.2539
	RE	0.0149	0.1141
7	BE	0.0282	0.3707
	LE	-0.0118	0.0723
	RE	0.0049	0.0226
8	BE	0.014	0.1651
	LE	-0.0429	0.3690
	RE	-0.0227	0.2032
9	BE	-0.0204	0.3122
	LE	0.0149	0.1274
	RE	0.0073	0.0940
10	BE	-0.0466	0.3982
	LE	0.049	0.2622
	RE	-0.0204	0.1509
11	BE	-0.0047	0.0744
	LE	-0.0577	0.3183
	RE	-0.0113	0.1236
12	BE	-0.0018	0.0247
	LE	-0.0308	0.3442
	RE	-0.0216	0.2441
13	BE	-0.0076	0.1028
	LE	-0.0318	0.2114
	RE	-0.0301	0.1966
14	BE	-0.0042	0.0845
	LE	-0.0696	0.2432
	RE	-0.0344	0.2837
15	BE	0.0262	0.3386
	LE	0.0105	0.1275
	RE	-0.0246	0.1529

*= Improved performance occurred if a Pearson Correlation value >0.433 was obtained for each participant.

3.3.2 Eye Position & Fixation Duration

The positions of the eyes were examined through the use of vergence angles as participants fixated on the needle. The fixation duration (time spent fixating at the needle) was also examined to see whether having additional somatosensory input would reduce fixation time during monocular viewing.

3.3.2.1 Fixation Duration at Needle

Fixation duration at the needle showed a main effect of viewing eye (F(2,26)=18.31, p<.0001). Post-hoc testing showed that fixation on the needle was significantly shorter during binocular viewing (1.569± 0.068s) in comparison to monocular viewing (left eye: 1.914 ± 0.072s; right eye: 2.077 ± 0.091s). No main effect was found for modality (F(1,13)=2.12, p=0.1694) indicating that fixation duration was comparable between the somatosensory (1.798 ± 0.073s) and vision only condition (1.909 ± 0.069s). The interaction between viewing eye and condition was also not significant (F(2,26)=0.05, p=0.9490), which indicates that somatosensory feedback did not differentially reduce the amount of time spent fixating on the needle during monocular or binocular viewing.

3.3.2.2 Vergence Angle & Vergence Specified Distance

Vergence angle at the needle showed a main effect of viewing eye (F(2,26)=13.75, p<.0001). The mean vergence angle during binocular viewing was 10.38° ± 0.30°, whereas during monocular viewing conditions the vergence angle was reduced (left eye viewing: 8.20° ± 0.39°; right eye viewing: 8.32° ± 0.31°). Figure 3.3 shows the vergence specified distance for each subject calculated using individual interpupillary distances (IPD) during binocular and monocular viewing conditions. The solid line plotted in the figure shows the line of unity for vergence specified distance obtained during binocular viewing. Since most of the data from the monocular condition fall above the line, vergence specified distance was greater during monocular viewing, which may have contributed to needle localization error in the depth axis away from the body.

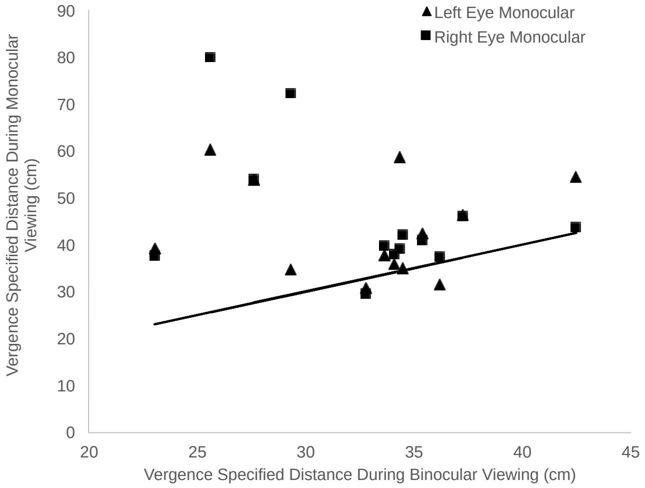


Figure 3.3: Mean vergence specified distance (VSD) for each participant during binocular and monocular viewing conditions when fixating on the needle. The regression line illustrates the line of unity; that is, equivalent VSD during binocular and monocular viewing. Data points above the line indicate a greater VSD during monocular as compared to binocular viewing and data points below the line indicate VSD nearer to the body.

There was no main effect of modality (F(1,13)=1.16, p=0.3001) for vergence (somatosensory: 9.03° ± 0.34°; vision only: 8.92° ± 0.32°) This indicates that somatosensory feedback did not significantly influence the vergence angle at the needle. The interaction between viewing eye and modality condition was also not significant (F(2,25)=0.88, p=0.4289) which indicates that the fixation location was similar across viewing conditions with somatosensory feedback (binocular: 10.33° ± 0.42°; left eye: 8.37° ± 0.57°; right eye : 8.30° ± 0.41°) and during the vision only condition (binocular: 10.43° ± 0.45°; left eye: 8.02° ± 0.55°; right eye: 8.34°± 0.48°).

3.3.3 Reaching Performance Measures

The Optotrak data were used to determine the contribution of somatosensory input specifying 3D needle location to task performance during monocular viewing. It was hypothesized that somatosensory feedback during monocular viewing would allow for shorter movement time (transport towards the needle) and a shorter placement time.

3.3.3.1 Movement Time (Transport to the Needle)

Movement time showed a main effect of viewing eye (F(2,28)=3.87, p=0.0328). Post hoc testing showed a significant difference between binocular viewing: 0.530 ± 0.015s and monocular left eye viewing (0.554 ± 0.018s), but not right eye viewing (0.538 ± 0.017s). More importantly, there was no main effect of modality (F(1,14)=0.94 p=0.3485; somatosensory: 0.539 ± 0.014s, vision only: 0.543 ± 0.014s. In contrast to our hypothesis, there was no significant interaction between viewing condition and modality (F(2,28)=0.79, p=0.4650).

3.3.3.2 Placement Time

A typical velocity profile for two cycles of reaching movements to the needle and to the bead during binocular and monocular viewing is shown in Figure 3.5. This figure clearly illustrates that somatosensory feedback facilitated bead placement on the needle during monocular viewing, which is demonstrated by shorter placement duration.

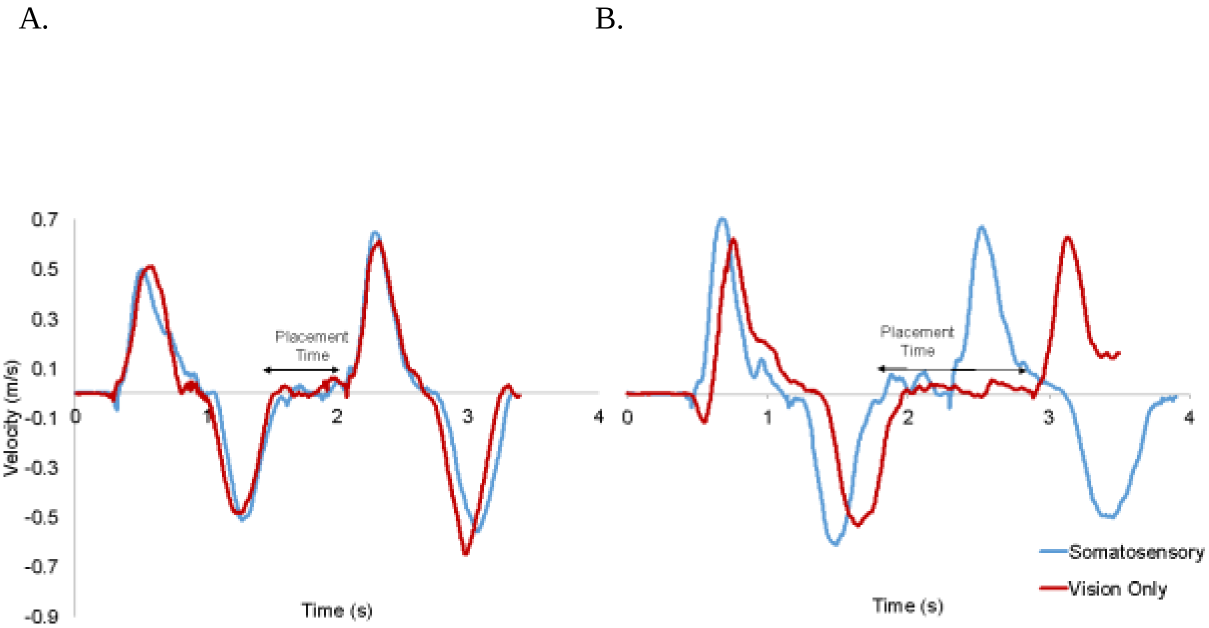


Figure 3.4: Reach velocity on a typical trial during binocular (A) and monocular (B) viewing with somatosensory or visual only feedback of the needle's location.

Results from the statistical analysis confirmed a main effect of viewing eye (F(2,28)=28.20, p<.0001). Post hoc testing showed a significant difference in placement duration during both monocular viewing conditions (left eye: 1.011 ± 0.046s; right eye: 0.980 ± 0.0341s) compared to binocular viewing (0.730 ± 0.030s). A main effect of modality was also significant (F(1,14)=37.15 p<.0001; somatosensory: 0.842 ± 0.031s; vision only: 0.971 ± 0.0378s). This demonstrates that having additional input through somatosensory feedback reduces placement time. In accordance with our hypothesis, the interaction between viewing condition and modality was also significant (F(2,28)=4.38, p=0.0022). Post-hoc testing revealed that the duration of the placement task was significantly shorter when somatosensory feedback was provided during monocular viewing (left eye: 0.921 ± 0.060s; right eye: 0.894 ± 0.044s) comparison to the vision only condition (left eye: 1.102 ± 0.063s; right eye: 1.065 ± 0.043s) (Fig 3.5). In contrast, placement duration during binocular viewing was not statistically different when somatosensory feedback was provided (0.711 ± 0.037s) and in the vision only condition (0.748 ± 0.048s).

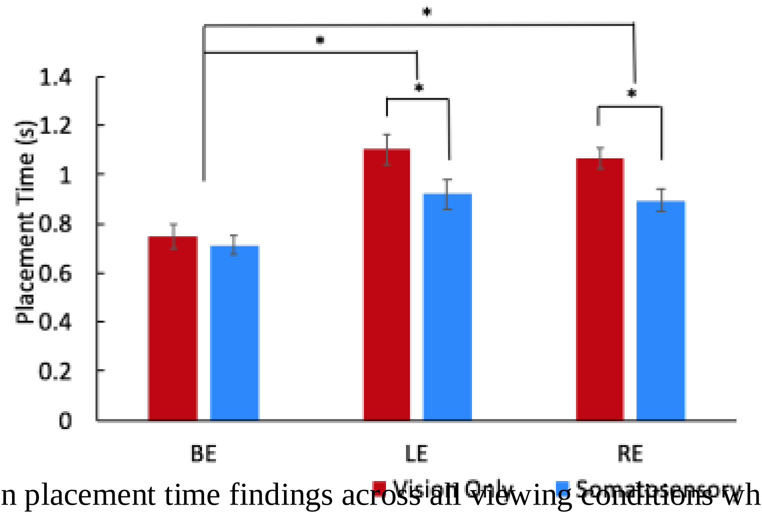


Figure 3.5: Mean placement time findings across all viewing conditions when somatosensory and visual only feedback is provided.

3.3.4 Kinematic Measures: Motor Planning and Execution

A shorter placement time during monocular viewing with somatosensory input raised the question regarding the contribution of somatosensory input toward motor planning and execution.

3.3.4.1 Kinematic Measure for Investigating Motor Planning

It was hypothesized that somatosensory input regarding the end location would improve movement planning, which would be reflected in higher peak accelerations, a trajectory biased towards the needle, and reduced variability in limb position at this time point.

Peak Acceleration

There was no significant main effect of viewing eye for peak acceleration (F(2,28)=1.75 p=0.1930); binocular viewing: 2872.51 ± 147.36 mm/s^2; left eye viewing: 2692.87 ± 136.84 mm/s^2; right eye viewing: 2695.44 ± 152.14 mm/s^2). Modality also showed no significant main effect (F(1,14)=2.77, p=0.1185) as mean peak acceleration with somatosensory feedback (2801.04 ± 118.65 mm/s^2) did not differ significantly from the vision only condition (2706.18 ± 118.86 mm/s^2). This indicates that the somatosensory feedback did not significantly benefit motor planning of the limb transport towards the needle. There was also no significant interaction between viewing condition and modality (F(2,28)=0.05, p=0.9552).

Limb Position at Peak Acceleration along Azimuth

No main effects of viewing eye, modality, or interaction were found for mean limb position or the spatial variability in limb position in the depth direction at peak acceleration.

Limb Position at Peak Acceleration along Depth

No main effects of viewing eye, modality, or interaction were found for mean limb position or the spatial variability in limb position in the depth direction at peak acceleration.

3.3.4.2 Kinematic Measures for Investigating Movement Execution – Online Control

It was hypothesized that somatosensory input will facilitate movement execution, as reflected by a bias in movement trajectory towards the needle and reduced variability in spatial limb position along both the azimuth (x) and depth (z) during limb trajectory.

The mean limb position and spatial variability of the limb were examined at various time points throughout the trajectory when reaching towards the needle. Examining limb position at 100 and 50 ms before and after PV, at PV, PD, and End of movement provides insight as to whether somatosensory input contributes to online control during movement execution.

Peak Velocity

There was a main effect of viewing eye for peak velocity (F(2,28)=4.22, p=0.0249. Post hoc testing showed a significant difference between binocular viewing (450.22 ± 21.55 mm/s) and monocular right eye viewing (left eye: 425.04 ± 21.43 mm/s, right eye: 416.60 ± 19.14 mm/s). However, there was no main effect of modality (F(1,14)=3.40 p=0.0864; somatosensory:

436.04 ± 17.33 mm/s, vision only: 425.20 ± 16.56 mm/s). There was also no significant interaction between viewing condition and modality (F(2,28)=0.09, p=0.9136).

Peak Deceleration

There was no significant main effect of viewing eye for peak deceleration (F(2,28)=0.80, p=0.4595); binocular viewing: 2955.62 ± 127.46 mm/s^2; left eye viewing: 2866.87 ± 154.98 mm/s^2; right eye viewing: 2767.44 ± 154.54 mm/s^2). Modality also showed no significant main effect (F(1,14)=0.39, p=0.5433) as mean peak deceleration with somatosensory feedback (2891.56 ± 124.12 mm/s^2) did not differ significantly from the vision only condition (2835.06 ± 114.28 mm/s^2). There was also no significant interaction between viewing condition and modality (F(2,28)=2.60, p=0.0923).

Limb Position along Azimuth

There was a main effect of viewing eye for mean limb position from 100 ms before PV to peak deceleration (for results from the statistical analysis see Table 3.2). Post hoc testing revealed a significant difference between right and left eye viewing conditions. A significant difference was also shown between binocular and right eye viewing conditions from PV to PD. As shown in Fig 3.6, the limb deviated to the right during left eye viewing, and to the left during right eye viewing in comparison to the binocular viewing condition.

There was a significant main effect of modality for mean limb position along the trajectory at PV, and at 50 ms after PV (for results from statistical analysis see Table 3.2). As shown in Fig 3.7, the limb deviated to the left (i.e., towards the needle, straight trajectory path) when somatosensory input was provided.

In contrast to our hypothesis, the interaction between viewing eye and modality showed no significant effect for mean limb position along the trajectory (Table 3.2).

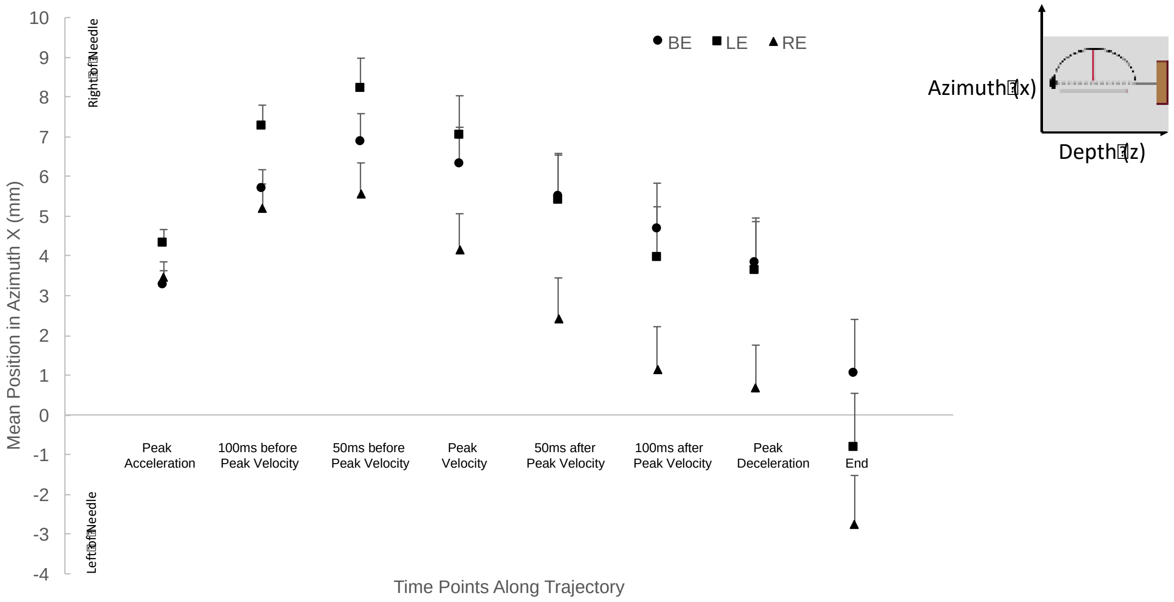


Figure 3.6: Mean limb position bias at various time points throughout the trajectory during binocular (BE), monocular left (LE) and right eye (RE) viewing along azimuth (x).

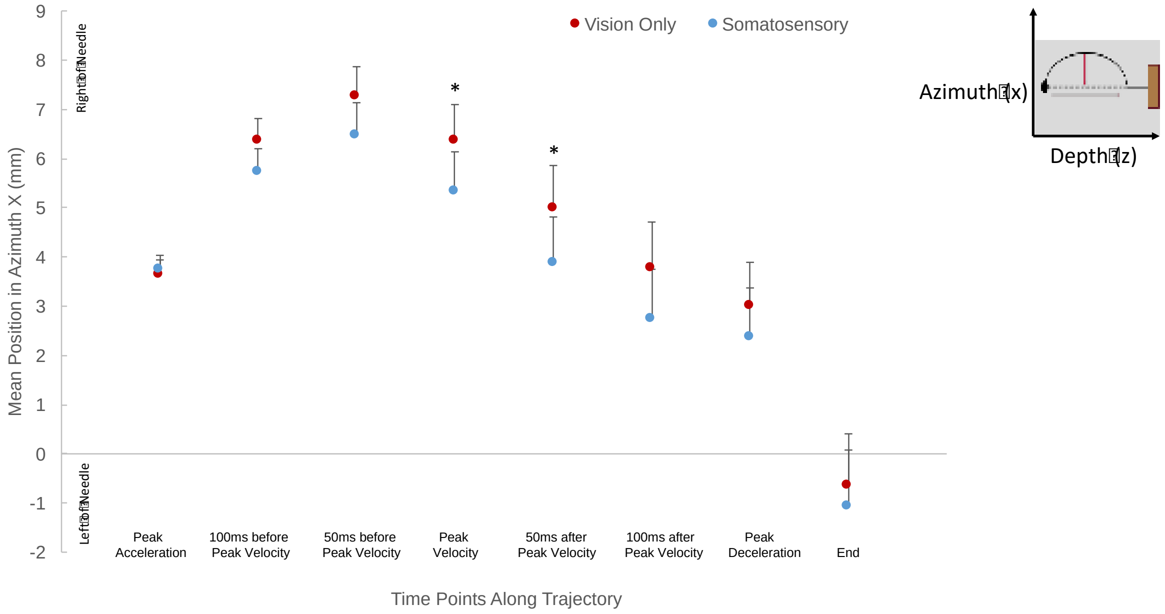


Figure 3.7: Mean limb position bias at various time points throughout the trajectory during vision only and somatosensory feedback conditions along azimuth (x).

Table 3.2: Statistical output for mean limb position at specific kinematic time points along azimuth

Outcome Measure	*Viewing Eye*	*Modality*	*Interaction*
100 ms before PV	**F(2,28)=4.58, p=0.0190)**	(F(1,14)= 3.42, p=0.0856)	(F(2,28)= 0.86 p=0.4347)
50 ms before PV	**F(2,28)=4.68, p=0.0176)**	(F(1,14)=4.15, p=0.0610)	(F(2,28)= 0.56, p=0.5766)
Peak Velocity	**F(2,28)=4.79, p=0.0163)**	**(F(1,14)=5.46, p=0.0348)**	(F(2,28)=0.93, p=0.4075)
50 ms after PV	**F(2,28)=4.19, p=0.0255)**	**(F(1,14)=4.98, p=0.0425)**	(F(2,28)=1.07, p=0.3562)
100 ms after PV	**F(2,28)=3.51, p=0.0436)**	(F(1,14)=3.10, p=0.1002)	(F(2,28)=0.77, p=0.4733)
Peak Deceleration	**F(2,28)=3.50, p=0.0438)**	(F(1,14)=1.15, p=0.3008)	(F(2,28)=1.29, p=0.2914)
End	F(2,28)=2.62, p=0.0908)	(F(1,14)= 0.56, p=0.4677)	(F(2,28)=0.72, p=0.4957)

Spatial Variability along Azimuth

The spatial variability of the limb position along azimuth showed a main effect of viewing eye at 100ms before PV. Post hoc testing revealed a significant difference between the two monocular viewing conditions. No main effect of modality was shown throughout limb trajectory. There was also no significant interaction between viewing eye and modality (for results from statistical analysis see Table 3.3).

Table 3.3: Statistical output for spatial limb variability at specific kinematic time points along azimuth

Outcome Measure	*Viewing Eye*	*Modality*	*Interaction*
100 ms before PV	**F(2,28)=3.69, p=0.0377)**	(F(1,14)=0.53, p=0.4785)	(F(2,28)=2.68 p=0.0859)
50 ms before PV	F(2,28)=2.10, p=0.1411)	(F(1,14)=0.11, p=0.7423)	(F(2,28)=1.12, p=0.3393)
Peak Velocity	F(2,28)=0.75, p=0.4836)	(F(1,14)=0.02, p=0.8900)	(F(2,28)=0.13, p=0.7501)
50 ms after PV	F(2,28)=0.07, p=0.9307)	(F(1,14)=0.01, p=0.9287)	(F(2,28)=0.35, p=0.7045)
100 ms after PV	F(2,28)=0.10, p=0.9048)	(F(1,14)=0.11, p=0.7418)	(F(2,28)=0.51, p=0.6088)
Peak Deceleration	F(2,28)=0.15, p=0.8654)	(F(1,14)=0.13, p=0.7218)	(F(2,28)=0.37, p=0.6931)
End	F(2,28)=0.14, p=0.8694)	(F(1,14)=0.67, p=0.4280)	(F(2,28)=0.11, p=0.8975)

Limb Position along Depth

There was a main effect of viewing eye for mean limb position along the trajectory 100 and 50ms before PV, at PV, after PV, PD and End of movement (Table 3.4). Post hoc testing showed a significant difference between left and right eye viewing, and a significant difference between binocular and monocular right eye viewing for the kinematic measures obtained at PV to the End. Figure 3.8 illustrates limb deviation towards the needle during right eye viewing and deviation away from the needle during left eye viewing.

There was no significant main effect of modality for mean limb position in depth at any time point along the trajectory. In contrast to our hypothesis, the interaction between viewing eye and modality showed no significant effect for mean limb position in depth, meaning that having somatosensory feedback under monocular viewing conditions did not affect limb trajectory towards the needle in depth (Table 3.4).

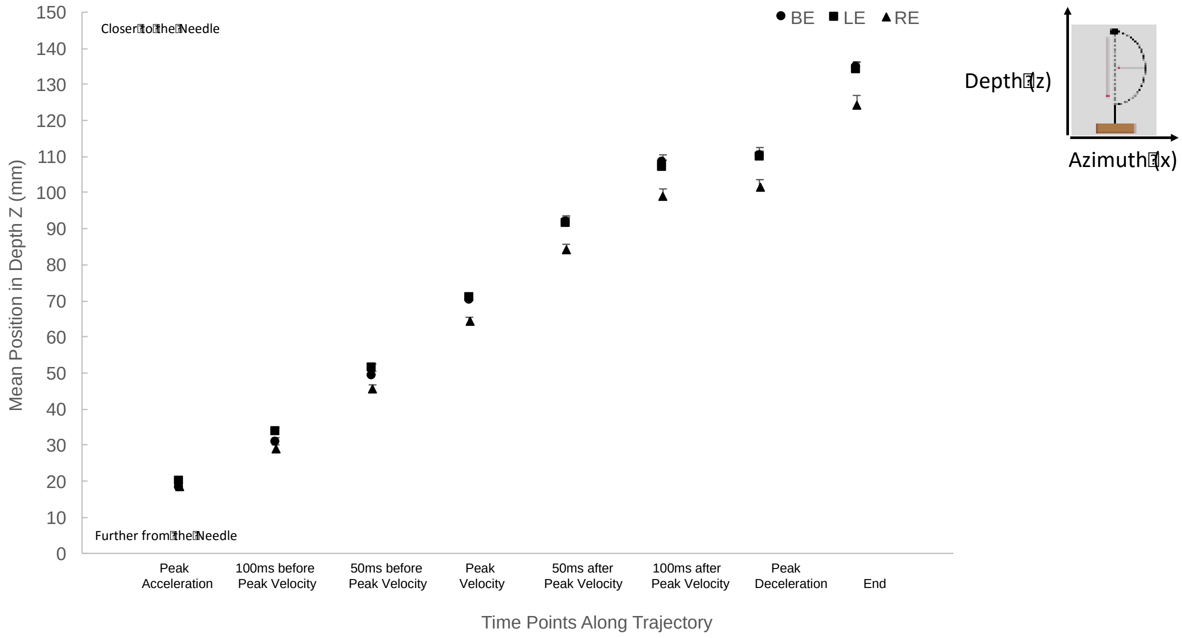


Figure 3.8: Mean limb position bias at various time points throughout the trajectory during binocular (BE), monocular left (LE) and right eye (RE) viewing along depth (z).

Table 3.4: Statistical output for mean limb position at specific kinematic time points along depth

Outcome Measure	*Viewing Eye*	*Modality*	*Interaction*
100 ms before PV	**(F(2,28)=5.83, p=0.0077)**	(F(1,14)=1.44, p=0.2504)	(F(2,28)=0.20, p=0.8226)
50 ms before PV	**(F(2,28)=6.54, p=0.0047)**	(F(1,14)=0.92, p=0.3543)	(F(2,28)=0.23, p=0.7990)
Peak Velocity	**(F(2,28)=6.68, p=0.0043)**	(F(1,14)=0.30, p=0.5948)	(F(2,28)=0.26, p=0.7701)
50 ms after PV	**(F(2,28)= 6.38, p=0.0052)**	(F(1,14)=0.01, p=0.9199)	(F(2,28)=0.25, p=0.7786)

100 ms after PV	**(F(2,28)= 6.14, p=0.0061)**	(F(1,14)=0.06, p=0.8123)	(F(2,28)=0.25, p=0.7796)
Peak Deceleration	**(F(2,28)= 3.73, p=0.0366)**	(F(1,14)=0.19, p=0.6708)	(F(2,28)=1.51, p=0.2382)
End	**(F(2,28)= 4.76, p=0.0166)**	(F(1,14)=0.21, p=0.6554)	(F(2,28)=0.47, p=0.6302)

Spatial Variability Along Depth

There were no main effects of viewing eye and modality for limb position variability along the trajectory in depth, however an interaction between viewing eye and modality was found (for results from statistical analysis see Table 3.5). The results showed increased variability in the right eye viewing condition when somatosensory feedback was unavailable. More specifically, right eye viewing at 50ms before PV (p=0.0465) showed a significant difference between the somatosensory and vision only conditions (Fig 3.9). In contrast, spatial limb variability was not significantly different between the modality conditions during left eye viewing (Fig 3.9).

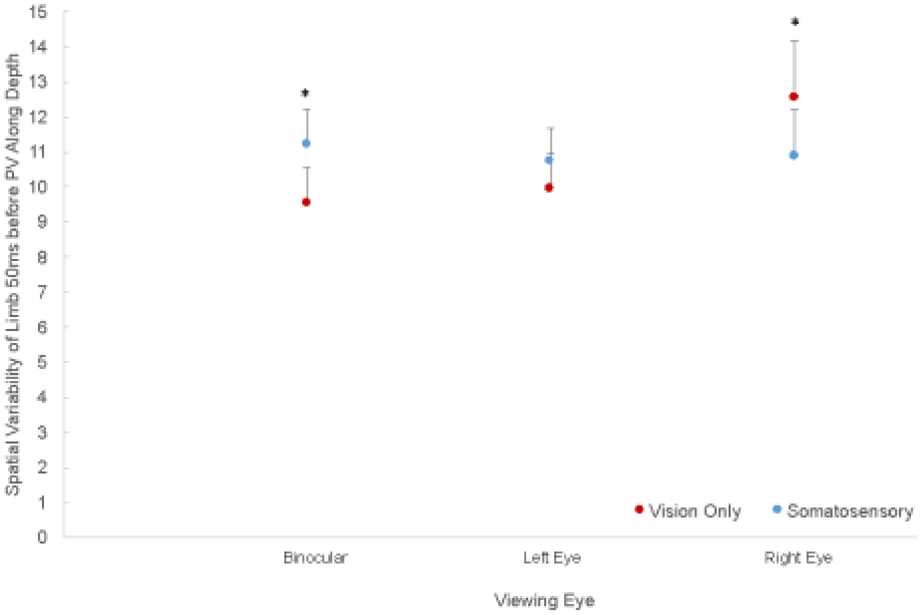


Figure 3.9: Spatial variability of limb at 50ms before peak velocity during binocular and monocular left eye, right eye along depth.

Table 3.5: Statistical output for spatial limb variability at specific kinematic time points along depth

Outcome Measure	*Viewing Eye*	*Modality*	*Interaction*
100 ms before PV	(F(2,28)=0.21, p=0.8121)	(F(1,14)=0.09, p=0.7634)	**(F(2,28)=3.81, p=0.0344)**
50 ms before PV	(F(2,28)=0.47, p=0.6282)	(F(1,14)=0.15, p=0.7052)	**(F(2,28)=4.61, p=0.0186)**
Peak Velocity	(F(2,28)=0.54, p=0.5881)	(F(1,14)=0.17, p=0.6891)	**(F(2,28)=4.28, p=0.0239)**
50 ms after PV	(F(2,28)=0.60, p=0.5567)	(F(1,14)=0.05, p=0.8343)	(F(2,28)=2.42, p=0.1073)
100 ms after PV	(F(2,28)=0.87, p=0.4292)	(F(1,14)=0.00, p=0.9504)	(F(2,28)=1.41, p=0.2616)
Peak Deceleration	(F(2,28)=2.40, p=0.1089)	(F(1,14)= 0.77, p=0.3942)	(F(2,28)=1.29, p=0.2920)
End	(F(2,28)=2.78, p=0.0792)	(F(1,14)=0.36, p=0.5604)	(F(2,28)=0.01, p=0.9883)

3.4 Discussion

To our knowledge, this study is the first to investigate how somatosensory input regarding target location affects the planning and execution of goal-directed movements when viewing monocularly. In order to examine the contribution of somatosensory input to 3D localization during monocular viewing, a complex bead-threading task was used. Our first hypothesis was supported, as the results showed shorter placement time when somatosensory information was provided during monocular viewing. To further investigate how this reduction took place, kinematic measures associated with motor planning and execution were examined. Our findings were not in accordance with the second hypothesis, as somatosensory input did not significantly affect motor planning in any viewing condition. Results provide some support for the third hypothesis because a straighter limb trajectory (i.e., less deviation along azimuth) was found across all viewing conditions when somatosensory input was available in comparison to the vision only condition. Overall, somatosensory input enhanced performance under monocular viewing conditions, which was evident when the limb reached the final stage of movement as the bead was placed onto the needle.

Somatosensory Input Improves Overall Performance

Understanding the contribution of the somatosensory system to target localization is important because this input may provide complementary and/or redundant information that could enhance performance of target localization. Our study showed significant improvement in placement time during monocular viewing when somatosensory feedback about needle location was provided through the contralateral limb. An improvement was also shown in placement time when viewing binocularly, however this improvement was relatively small and not statistically significant. A potential explanation could be that sensory information from each modality is weighted proportionally to its reliability (i.e., the inverse of standard deviation) (Ernst & Banks, 2002). During binocular viewing, the cue of ocular vergence may be weighted more heavily than the input from the somatosensory system. The cue of ocular vergence plays a vital role in depth perception, as it provides depth information for planning the reach transport component during movement (Melmoth et al., 2007) and is the most reliable input in the near, peripersonal space (Tresilian et al. 1999). When viewing monocularly, the cue of ocular vergence becomes disrupted due to phoria, which is a deviation of the covered eye (Ono & Gonda, 1978; Ono & Weber, 1981; Park & Shebilske, 1991). When the vergence signal is unreliable or weak, another modality like the somatosensory system may significantly contribute and improve target localization. Previous literature has shown reduced reliance on visual information when having to determine limb position when the amount of visual information provided about the environment was reduced (Mon-Williams et al., 1997). Similarly, when reducing the visual cue of ocular vergence through monocular viewing conditions, the ability to localize a targets position becomes hindered; therefore the system may rely more heavily on the somatosensory modality. More specifically, planning the upcoming movement with regards to target location would rely more on the somatosensory modality from the limb that is in direct contact with the target, as the input from monocular vision would provide less reliable input. Therefore, reduced visual information may cause a shift in weighting towards the more reliable modality in order to improve target localization in 3D space.

Our second performance measure of movement time, showed no significant difference when somatosensory feedback was present. This finding was not in accordance with our hypothesis, as it was believed that having somatosensory input would improve target localization and thus contribute to faster movement times. This finding could be attributed to the influence of target modality on planning of reaching movements. Previous studies have shown that when reaching towards a visual target, the input from the proprioceptive modality is less important than that of the visual modality (Sarlegna & Sainburg, 2006; Sober & Sabes, 2005). More specifically, a shift in visual feedback regarding hand position only affected reach planning when the target was visual, whereas minimal effects were found when the target was proprioceptively defined (Sarlegna & Sainburg, 2006). In our study, the target was defined through the visual and somatosensory modalities simultaneously. Therefore, it may be that the CNS choses to avoid transforming between coordinate frames and relies predominately on visual input about target position, as this input was also present throughout the somatosensory condition. This would then explain why no evidence was found to support faster movement times when somatosensory input was provided.

Somatosensory Input does not Influence Motor Planning

Peak acceleration is a valid indicator of the initial motor plan as it occurs early during the trajectory (i.e., within 100 msec after movement onset), which is mainly under open-loop control (Jeannerod., 1991; Servos et al., 1992). When looking at our results, there was no significant effect of somatosensory input specifying needle location on peak acceleration, or limb position at peak acceleration. It was hypothesized that having input from the right limb regarding target location would improve motor planning, due to greater certainty in where the targets position lied, however this was not evident in our findings. It is possible that the lack of effect of modality condition is due to the difficulty in transforming the somatosensory input into a common coordinate frame. More specifically, visual input about target location is encoded in a retinocentric frame of reference (Crawford, Medendorp, & Marotta, 2004; Desmurget et al., 1995; Snyder, Batista & Anderson, 2000), whereas somatosensory input is in a shoulder-centered coordinate frame (Desmurget et al., 1998). In order to optimally combine the inputs from each of these modalities, the brain must use a common coordinate frame. However, when transforming the signal from one coordinate frame to another, errors in mapping target location or in the computation can occur (Sober et al., 2003). Not only are these potential errors costly, but also this complex transformation between coordinate frames may require practice. It is possible that the CNS requires practice, or ‘training’ in order to reduce errors in transformation, and thus use the additional modality to accurately plan the upcoming movement.

Overall, the findings in our study did not show evidence to support that somatosensory input contributes to motor planning during this complex task. In order to investigate whether practice can help reduce noise when transforming between coordinate frames, the effect of practice will be examined further in study two.

Somatosensory Input Affects the Control of Limb Trajectory along Azimuth

Somatosensory input plays a critical role in the online control of reaching movements (Prablanc & Martin, 1992). The input from the somatosensory modality provides the CNS with information regarding the spatial location of body segments in space. As hypothesized, results from the study showed a significantly closer limb trajectory towards the needle along azimuth at peak velocity and 50ms after peak velocity, when somatosensory input was provided. Interpreting these findings in the context of previous studies is difficult as most literature about online control of reaching movement is based on the analysis of reaching towards visually defined targets. For example, a recent study manipulated the time at which visual input was presented throughout limb movement in order to understand when visual input is required during reach execution (Tremblay, Crainic, & Grosbois, 2016). This study found that visual input during the early stage of movement allows for more efficient online corrections compared to a condition when vision was provided in the later stages of the trajectory (Tremblay et al., 2016). More specifically, visual information was necessary from movement onset to peak velocity for more efficient online limb-target regulation. To our knowledge no previous studies examined the time course of when somatosensory is used for online control of limb trajectory.

Within our study, somatosensory input from both, the reaching limb and the contralateral limb in contact with the target (needle), provided task-relevant sensory information. When reaching towards a visual target, the CNS must integrate visual information about extrinsic spatial coordinates of target location and input from the somatosensory system about intrinsic body segments of the reaching limb (Sainburg et al., 2002). Similarly, the CNS would need to combine the input from the visual and somatosensory modalities about target location into one coordinate frame. Results from this study showed that somatosensory input about target location had a significant effect on limb trajectory only around the time of peak velocity. Therefore, the presence of this additional input had a limited effect on the control of limb trajectory. It is possible that the process of transforming sensory inputs into a common coordinate frame for the control of reaching and for target localization may be computationally taxing for the CNS during this complex task (Sabes et al., 2003). Due to these costly transformations, the CNS may select to use the input from each modality at a specific time point in the trajectory rather than integrating these inputs throughout the trajectory. In other words, it is possible that the CNS relies predominantly on comparing visual-to-visual input and somatosensory-to-somatosensory input at certain time points during the execution of this task. This would reduce the computational cost and potentially the amount of noise that is created when transforming between the coordinate frames.

Somatosensory Input did not help to reduce Spatial Variability along Depth

It was hypothesized that providing somatosensory input will lead to reduced variability in limb trajectory during movement execution. Although our findings showed a significant interaction at three time points: 100ms before PV, 50ms before PV and PV, these findings were opposite to our hypothesis. Specifically, there was no change in limb spatial variability between the viewing conditions when somatosensory feedback was provided. Instead, results showed increased spatial variability when viewing with the right eye without the somatosensory input. It is important to note that this effect was not demonstrated during binocular, or left eye viewing. When one eye is covered, phoria disrupts the ocular vergence cue, which is an important cue for target localization, and this could lead to aiming errors (Mon-Williams and Dijkerman 1999; Melmoth et al. 2007). Analysis of eye position data in our study showed a significant vergence error when subjects fixated on the needle. Specifically, the vergence posture was diverged during monocular viewing as indicated by a smaller vergence angle, suggesting exophoria of the covered eye. It might be expected that greater amount of phoria in the left eye could lead to greater variability in limb trajectory when viewing monocularly with the right eye. However, our analysis showed no difference in vergence error between the right and left eye viewing conditions, suggesting that the amount of phoria in the left and right eye during monocular viewing was comparable. Therefore, the analysis conducted to date offers no explanation as to why there was increased limb trajectory variability during right eye viewing.

In conclusion, our study showed that somatosensory feedback helped reduce placement time during monocular viewing. To further examine how this enhanced performance occurred, the contribution of the somatosensory modality towards motor planning and execution were investigated. There was no significant evidence to support that the somatosensory input was used to improve motor planning; however, movement execution was affected because the limb deviated closer to the needle along azimuth around the time of peak velocity. Within our study were two major limitations: lack of standardized practice and visibility of the limb providing localization information. The next study was designed to address these limitations by further investigating the effects of practice, and the contribution of the somatosensory modality to goal-directed movement when visual feedback about the limb holding the target is removed.

Section 4: Study 2 - The Contribution of Visual and Somatosensory Input Regarding 3D Location for the Performance of a Precision Grasping and Placement Task in Adults without Visual Feedback of the Limb

4.1 Introduction

Binocular vision provides the most accurate and precise depth information; however, many people have impairments in binocular visual function. Our first study investigated whether somatosensory input improves target localization during the performance of a precision grasping and placement task. The results of this study indicated that somatosensory feedback reduced the duration of the placement task, specifically under monocular viewing condition. This finding corresponds to previous literature that shows the benefit of visual-somatosensory integration towards localization (Nardini et al., 2013). Thus, the purpose of the second study was to determine whether somatosensory feedback without a concurrent view of the limb will facilitate performance such as that found in study one.

Study 2 also examined the effects of adding additional practice trials on the performance of the bead-threading task. Central tendency and variability of performance of upper limb tasks are both influenced by practice. After moderate practice of a typical aiming task, participants establish a more consistent movement pattern characterized by optimized speed, accuracy and energy expenditure (Elliott et al., 2009). Thus, participants in the second study were tested on the bead-threading task after they had an opportunity to practice the task and found a strategy to perform the task consistently.

It was hypothesized that somatosensory feedback will contribute towards localization of the needle, which is similar to the findings from the first study. Specifically, somatosensory feedback specifying needle 3D location, without the sight of the limb providing somatosensory feedback, will facilitate the placement task in comparison to the vision only condition. This will be indicated by a shorter time to complete the placement task specifically during monocular viewing. It was also hypothesized that with the additional practice somatosensory input regarding the end location will facilitate movement planning. This will be reflected in higher peak acceleration and reduced variability in limb position at this time point. Lastly, somatosensory input will improve movement execution, as reflected by a shift of the trajectory in direction towards the needle and reduced variability in the spatial position of the limb throughout the trajectory.

4.2 Methods

4.2.1 Participants

Fifteen students from the University of Waterloo (9 females, mean age= 22.6 ± 2.32 years) participated in the study. Five of the fifteen subjects that took part in this study were participants in study 1. All subjects were right hand dominant and ten were right eye dominant. All participants had self- reported normal, or corrected-to-normal vision with no history of visual, or ocular abnormalities. Eye dominance was determined through eye preference when looking through a tube and by pointing to a corner of a room and closing one eye at a time. All participants had normal visual acuity in each eye and stereoacuity of at least 40 secs of arc at 16inches, which was measured using the Randot Stereoacuity Booklet (Randot SO-002 test). Fusional vergence and amplitude of accommodation eye tested were also administered. Each participant gave informed consent. This study also received approval by the Research Ethics Board at the University of Waterloo.

4.2.2 Materials and Procedure

The methods of study 2 were similar to that of study 1 except for two differences. The first difference is that there were fifteen trials within each viewing condition. The first five trials in each condition were practice trials. Another difference is that during the entire protocol subjects were unable to see their left hand, which was holding the needle. The hand was hidden using a white cardboard cutout that attached to the needle apparatus, so that subjects could still grasp the needle during somatosensory feedback trials without seeing their hand. During the vision only conditions, the left hand was placed on the table top, which was once again under the board and out of sight for each participant. The second major difference between studies is that the needle was less than half an arm's length for study number two. The reason being is that the apparatus did not allow for further distances without the left hand being visible to the subject, thus the distance from chin rest to needle ranged from distances of 20-27cm.

Figure 4.1: Experimental set-up illustrating the location of the bead-board and the vertical needle with no visual capture of the limb during somatosensory and no somatosensory feedback trial conditions

All instrumentation was similar to that of study 1. The main difference between the studies is that a white cardboard (31x24cm) which was placed onto the needle and attached on the other side to a small, square-shaped wooden stand. This allowed the participant's left hand to be hidden during data collection.

4.2.3 Data Reduction

4.2.3.1 Eye Position Data Reduction

Four subjects were excluded due to unreadable eye tracking data. Any trials where the bead was dropped were also excluded from the analysis (appendix C1). Eye position traces were examined similar to that of study 1; fixation on the target was determined using a velocity criterion, that is, fixation on the target was defined as stable when the velocity <20 deg/s.

The mean vergence angle was calculated by subtracting the left eye from the right eye. The vergence angle obtained for each subject was used to calculate the vergence specified distance (VSD) for fixation on the needle. VSD was calculated for each subject using their individual interpupillary distance (IPD) (i.e., VSD = IPD / tan [vergence angle], where vergence angle = left eye position- right eye position) (Howard and Rogers 2002).

4.2.3.2 Optotrak Data Reduction

Only successful trials, where no beads were dropped or there was no loss of finger tracking, were included in the kinematic analysis. Similar to study 1, we focused on only two phases: transport towards the needle and placement time. The start of the transport phase to the needle was defined as when velocity reached at least 20mm/s for 20 consecutive milliseconds in the direction of the needle, with the end of the movement defined as velocity falling under 100mm/s for 20 consecutive milliseconds after peak velocity.

In addition to the standard kinematic measure, the mean position and variability of the limb at peak acceleration (PA), peak velocity (PV), peak deceleration (PD), and at the end were also examined to test our second and third hypotheses. Peak acceleration was defined as the maximum value obtained from the acceleration data that fell between movement start and the time of peak velocity. Similarly, peak deceleration value was defined as the minimum value obtained from the acceleration data that fell between the peak velocity time and movement end. Rather than restricting kinematic analysis to four distant points (PA, PV, PD, End), addition time points within the trajectory were investigated. The position of the limb at 50ms and 100ms intervals proceeding and following PV were examined to provide a better understanding as to how sensory input may vary throughout a continuous movement.

4.2.4 Statistical Analysis

4.2.4.1 Eye Position Analysis

The mean fixation duration across each viewing condition (binocular, monocular left eye, right eye) was calculated for each modalities condition (vision only, somatosensory) for all participants.

All data were approximately normally distributed which was confirmed using a visual approach, that is, stem and leaf plots and qq plots. Mean maximum duration and mean vergence were examined using a repeated measures Analysis of Variance (ANOVA) with 2 within-subject factors: Modality (somatosensory, vision only) and Viewing Conditions (binocular, monocular left, monocular right). A post hoc Tukey test was done to determine were significance lies between means. All outcome measures were reported using means and standard deviations.

4.2.4.2 Optotrak Data Analysis

All data were approximately normally distributed, which was confirmed by examining outliers through skewness and kurtosis (appendix C3), and through a visual approach, that is, stem and leaf plots and qq plots. All dependent measures were submitted to repeated measures Analysis of Variance (ANOVA) with 2 within-subject factors: Modality (somatosensory, vision only) and Viewing Conditions (binocular, left eye, right eye).

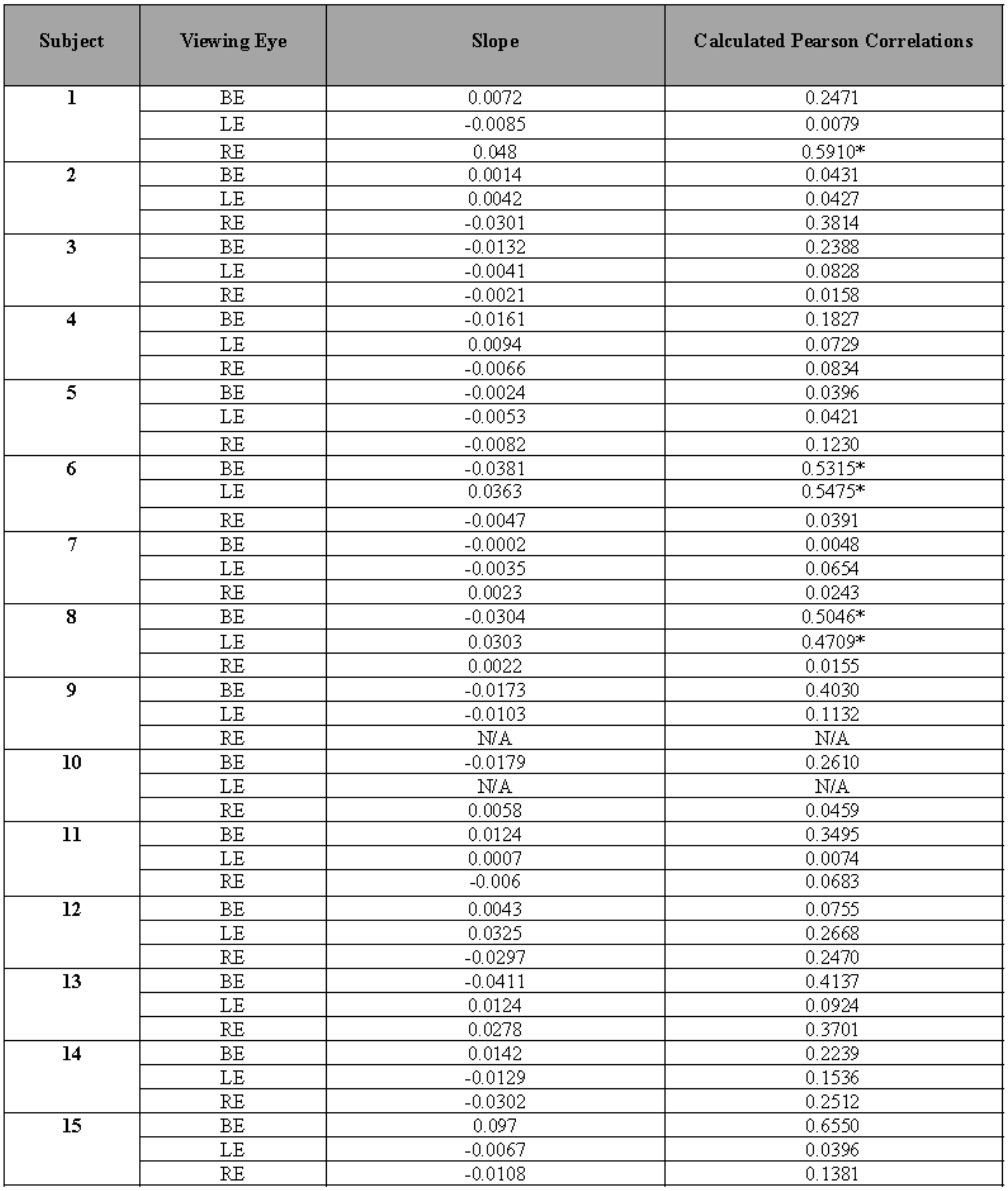
The spatial variability of the limb throughout reaching was analyzed in the azimuth (x) and depth (z) direction of movement at the following kinematic markers: for PA, PV, PD, End as well as 50 and 100 mm/s before and after PV. These dependent measures were submitted to a repeated measures Analysis of Variance (ANOVA) with 2 within-subject factors: Modality (somatosensory, vision only) and Viewing Conditions (binocular, left eye, right eye).

4.3 Results

4.3.1 Effects of Practice

In study one, a potential limitation was the effect of practice from the first to last trial. In order to address the effect of practice, participants performed 5 practice trials prior to the 10 experimental trials. Trials one to ten were plotted for all fifteen subjects (appendix D). The slope and Pearson's correlation values were examined for each participant and viewing condition to determine whether an improvement in placement time was statistically significant. In order to reach statistical significant (df=19 and $p<0.05$), a Pearson r value of 0.433 needed to be reached. Significant improvement from first to last trial was found in several conditions (Table 4.1).

Table 4.1: Pearson correlation and slope values for each participant during binocular and monocular viewing conditions.



Subject	Viewing Eye	Slope	Calculated Pearson Correlations
1	BE	0.0072	0.2471
	LE	-0.0085	0.0079
	RE	0.048	0.5910*
2	BE	0.0014	0.0431
	LE	0.0042	0.0427
	RE	-0.0301	0.3814
3	BE	-0.0132	0.2388
	LE	-0.0041	0.0828
	RE	-0.0021	0.0158
4	BE	-0.0161	0.1827
	LE	0.0094	0.0729
	RE	-0.0066	0.0834
5	BE	-0.0024	0.0396
	LE	-0.0053	0.0421
	RE	-0.0082	0.1230
6	BE	-0.0381	0.5315*
	LE	0.0363	0.5475*
	RE	-0.0047	0.0391
7	BE	-0.0002	0.0048
	LE	-0.0035	0.0654
	RE	0.0023	0.0243
8	BE	-0.0304	0.5046*
	LE	0.0303	0.4709*
	RE	0.0022	0.0155
9	BE	-0.0173	0.4030
	LE	-0.0103	0.1132
	RE	N/A	N/A
10	BE	-0.0179	0.2610
	LE	N/A	N/A
	RE	0.0058	0.0459
11	BE	0.0124	0.3495
	LE	0.0007	0.0074
	RE	-0.006	0.0683
12	BE	0.0043	0.0755
	LE	0.0325	0.2668
	RE	-0.0297	0.2470
13	BE	-0.0411	0.4137
	LE	0.0124	0.0924
	RE	0.0278	0.3701
14	BE	0.0142	0.2239
	LE	-0.0129	0.1536
	RE	-0.0302	0.2512
15	BE	0.097	0.6550
	LE	-0.0067	0.0396
	RE	-0.0108	0.1381

*= Improved performance occurred if a Pearson Correlation value >0.433 was obtained for each participant.

4.3.2 Eye Position & Fixation Duration

The positions of the eyes were examined using the vergence angle when participants fixated on the needle location. Fixation duration was also examined as the time spent fixating on the needle during each position in order to determine whether somatosensory input reduced fixation time during monocular viewing.

4.3.2.1 Maximum Fixation Duration at Needle

The maximum duration spent fixating at the needle showed a main effect of viewing eye (F(2,19)=10.27, p=<.0009). Post-hoc testing showed that fixation on the needle was significantly shorter during binocular viewing (1.240 ± 0.058s) in comparison to monocular viewing (left eye: 1.610 ± 0.090s; right eye: 1.590 ± 0.071s. No main effect was found for modality (F(1,11)=0.46, p=0.5099) indicating that fixation duration was comparable between the somatosensory (1.440 ± 0.074s) and vision only condition (1.490± 0.058s). The interaction between viewing eye and condition was also not significant (F(2,19)=0.09, p=0.9117), which indicates that somatosensory feedback did not significantly reduce the amount of time spent fixating on the needle in either viewing condition.

4.3.2.2 Vergence Angle & Vergence Specified Distance

Vergence angle at the needle showed a main effect of viewing eye (F(2,17)=13.34, p=0.003). The mean vergence angle during binocular viewing was 12.06° ± 0.41°, whereas during monocular viewing conditions the vergence angle was reduced (left eye: 8.90° ± 0.60°;

right eye: 9.54° ± 0.66°). Figure 3.4 shows the vergence specified distance for each subject calculated using individual interpupillary distances (IPD) during binocular and monocular viewing conditions. The line plotted in the figure shows the line of unity for vergence specified distance obtained during binocular viewing. Since most of the data from the monocular conditions fall above the line, vergence specified distance was greater during monocular viewing, which may have contributed to needle localization error in the depth axis away from the body.

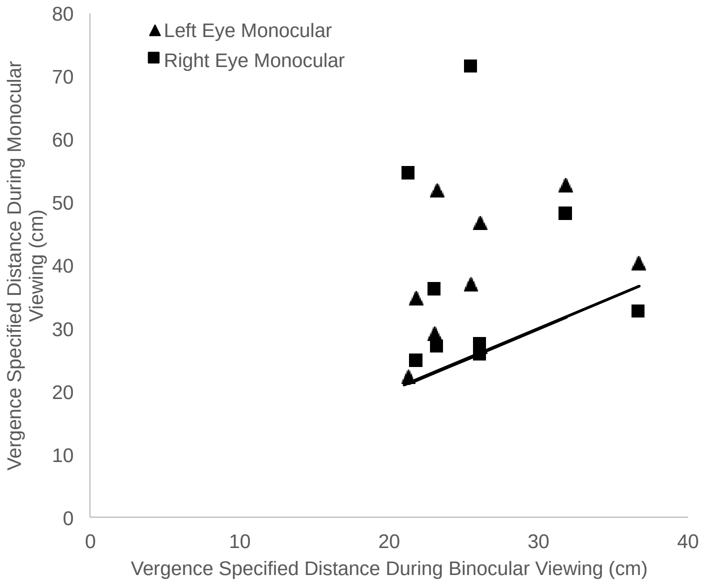


Figure 4.2: Mean vergence specified distance (VSD) for each participant during binocular and monocular viewing conditions when fixating on the needle. The regression line illustrates the line of unity; that is, equivalent VSD during binocular and monocular viewing. Data points above the line indicate a greater VSD during monocular as compared to binocular viewing and data points below the line indicate VSD nearer to the body.

No main effect was found for modality (F(1,10)=0.15, p=0.7065; somatosensory: 10.01° ± 0.56°; vision only: 10.28° ± 050°). This indicates that somatosensory feedback did not significantly reduce the vergence angle at the needle. The interaction between viewing eye and condition was also not significant (F(2,14)=2.26, p=0.1412). Therefore, this shows that the vergence angle was similar during left eye and right eye viewing with somatosensory feedback (left: 8.79° ± 0.92°; right: 9.40° ± 0.93°) and during the vision only condition (left: 8.99° ± 0.82°; right: 9.68°± 0.99°). Similarly, there was no effect during binocular viewing; somatosensory (12.15° ± 0.68°) and vision only condition (11.99° ± 0.54°).

4.3.3 Reaching Performance Measures

The Optotrak data were used to determine the contribution of somatosensory input specifying 3D needle location to task performance during monocular viewing. It was hypothesized that somatosensory feedback during monocular viewing would lead to shorter movement time (transport towards the needle), and faster placement times.

4.3.3.1 Movement Time (Transport to the Needle)

Movement time showed a main effect of viewing eye (F(2,26)=5.77, p=0.0084; binocular viewing: 0.478 ± 0.015s; left eye: 0.499 ± 0.016s, right eye: 0.490 ± 0.013s) and a main effect of modality (F(1,14)=7.35 p=0.0169; somatosensory: 0.481 ± 0.011s, vision only: 0.496 ± 0.012s). In contrast to our hypothesis, there was no significant interaction between viewing condition and modality (F(2,26)=0.59, p=0.5615).

4.3.3.2 Placement Time

Results from the statistical analysis confirmed a main effect of viewing eye (F(2,26)=26.18, p<.0001). Placement duration was longer during monocular viewing (left eye: 0.743 ± 0.028s; right eye: 0.763 ± 0.030s) compared to binocular viewing (0.545 ± 0.020s). A main effect of modality was also significant (F(1,14)=5.93 p=0.0288; somatosensory: 0.663 ± 0.023s; vision only: 0.699 ± 0.028 s). This demonstrates that having additional input through somatosensory feedback reduces placement time. In contrast to the hypothesis, there was no interaction between viewing condition and modality (F(2,26)=1.12, p=0.3417).

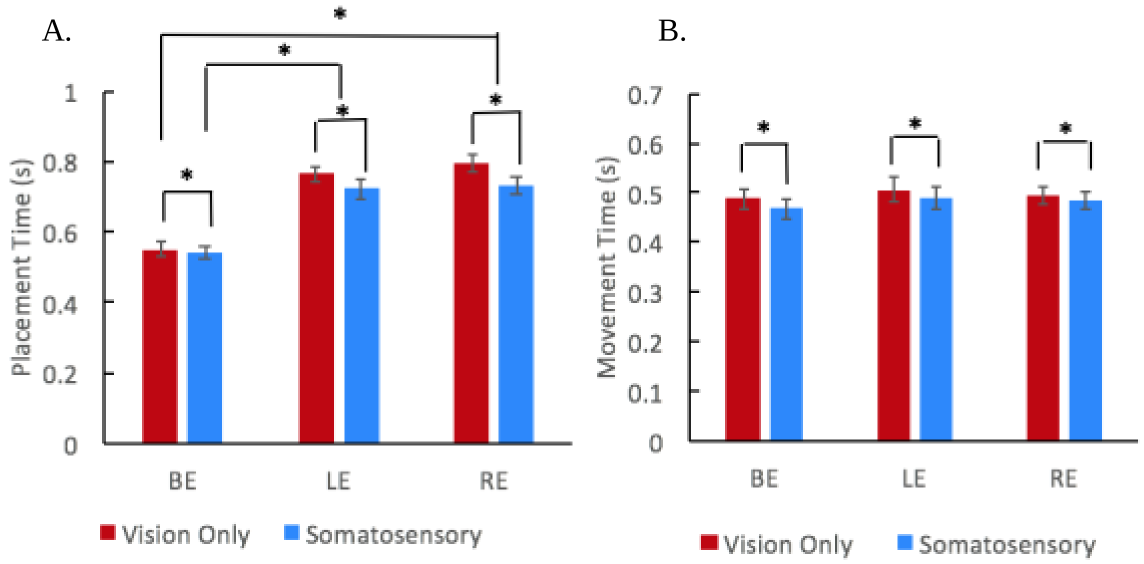


Figure 4.3 –Mean placement time (A), and movement time (B) during each viewing conditions when visual only and somatosensory feedback are provided.

4.3.4 Kinematic Measures: Motor Planning and Execution

It was hypothesized that somatosensory input regarding the target location would improve reach planning, which would be reflected in higher peak accelerations, greater bias towards the needle, and reduced variability in limb position at this time point.

4.3.4.1 Kinematic Measure for Investigating Motor Planning

Peak Acceleration

Peak acceleration showed a significant main effect of viewing eye (F(2,26)=8.16, p=0.0018); binocular viewing: 4105.99 ± 289.95 mm/s^2; left eye viewing: 3587.71 ± 296.12 mm/s^2; right eye viewing: 3599.43 ± 261.23 mm/s^2). Modality also showed a main significant effect (F(1,14)=4.64, p=0.0491). Peak acceleration with somatosensory feedback (3883.15 ± 237.06 mm/s^2) was significantly higher compared to the vision only condition (3661.50 ± 226.56 mm/s^2). This indicates that the somatosensory feedback contributed to planning of the reach towards the needle. In contrast to our hypothesis, there was no significant interaction between viewing condition and modality (F(2,26)=1.17, p=0.3247).

Limb Position at Peak Acceleration along Azimuth and Depth

No main effects of viewing eye, modality, or interaction were shown for limb position in the depth direction at peak acceleration.

Spatial Variability of Limb along Azimuth and Depth

No main effects of viewing eye, modality, or interaction were shown for limb position in the azimuth or depth at peak acceleration.

4.3.4.2 Kinematic Measure for Investigating Movement Execution – Online control

Mean limb position and variability were examined at various time points throughout the trajectory when reaching towards the needle. Examining 100 and 50 ms before and after PV, PV, PD, and End of movement provides insight as to whether somatosensory input contributes to movement execution. It was hypothesized that somatosensory input would benefit movement execution as reflected by a bias in movement trajectory towards the needle and reduced variability in spatial limb position during reaching in both the azimuth (x) and depth (z) directions.

Peak Velocity

There was a main effect of viewing eye for peak velocity (F(2,26)=5.77, p=0.0084; binocular viewing: 530.15 ± 27.40 mm/s; left eye: 492.68 ± 28.60 mm/s, right eye: 504.68 ± 25.79 mm/s). There was also a main effect of modality (F(1,14)=7.35 p=0.0169; somatosensory: 520.10 ± 19.86 mm/s, vision only: 499.18 ± 22.28 mm/s), indicating that having somatosensory input was associated with a higher reach peak velocity. In contrast to our hypothesis, there was no significant interaction between viewing condition and modality (F(2,26)=0.59, p=0.5615).

Peak Deceleration

There was no significant main effect of viewing eye for peak deceleration (F(2,26)=3.38, p=0.0495); binocular viewing: 3677.54 ± 270.26 mm/s^2; left eye viewing: 3207.85 ± 265.46 mm/s^2; right eye viewing: 3318.47 ± 213.07 mm/s^2). Modality also showed no significant main effect (F(1,14)=2.29, p=0.1521) as mean peak deceleration with somatosensory feedback (3477.41 ± 214.44 mm/s^2) did not differ significantly from the vision only condition (3338.01 ± 197.62 mm/s^2). There was also no significant interaction between viewing condition and modality (F(2,28)=0.47, p=0.6298).

Limb Position along Azimuth

There was a main effect of viewing eye for mean limb position along the trajectory 50 ms before PV, 100 before PV, at PV, 50 ms after PV and 100 ms after PV (Table 4.2). As shown in Fig 4.4, the limb deviated to the right during left eye viewing, and to the left during right eye viewing in comparison to the binocular viewing condition. There was no significant effect of viewing eye for the latter kinematics (100 ms after PV, PD, End).

There was a significant main effect of modality for mean limb position along the trajectory at 50 and 100 ms after PV (Table 4.2). As shown in Fig 4.5, the limb deviated to the left (i.e., towards the needle, straight trajectory path) when somatosensory input was provided.

In contrast to our hypothesis, the interaction between viewing eye and modality showed no significant effect for mean limb position (Table 4.2).

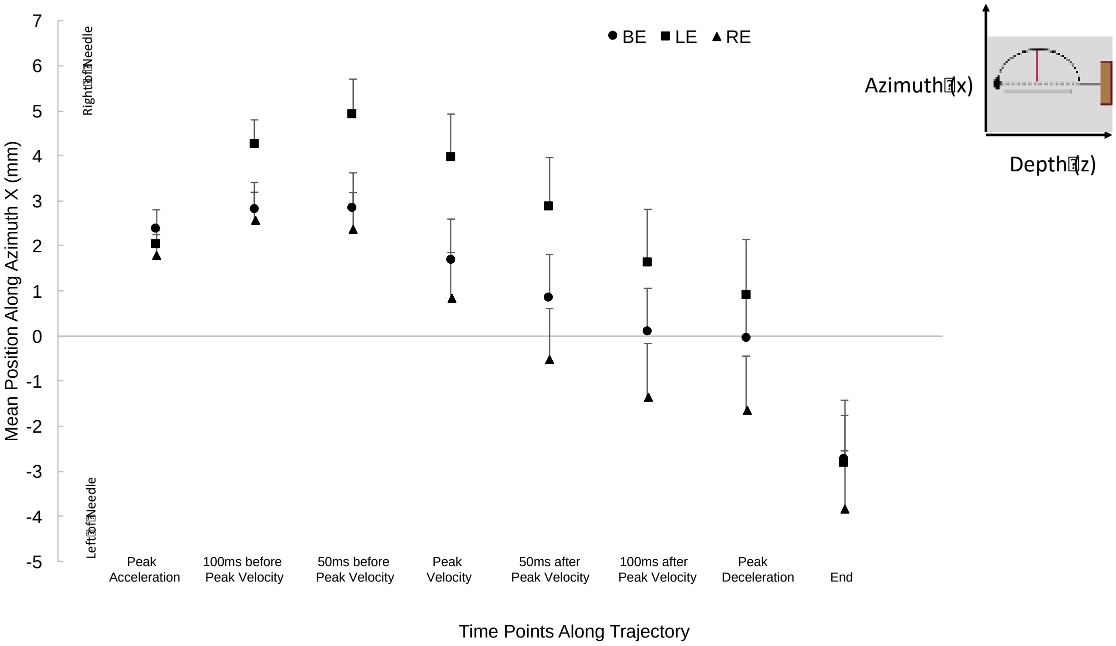


Figure 4.4: Mean limb position bias at various time points throughout the trajectory during binocular (BE), monocular left (LE) and right eye (RE) viewing along azimuth (x).

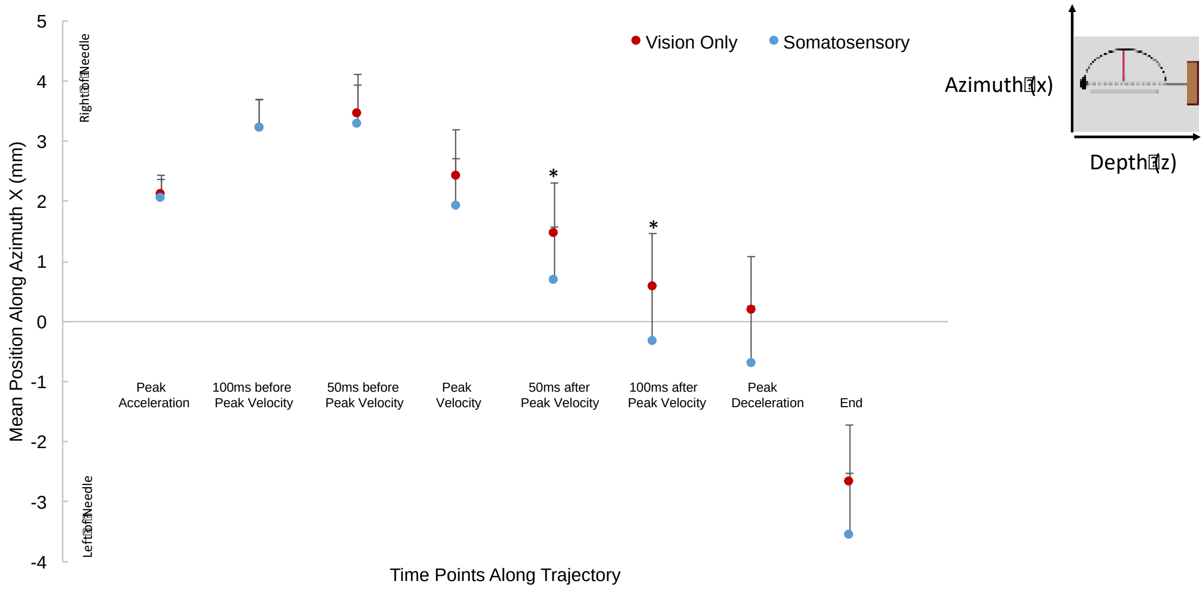


Figure 4.5: Mean limb position bias at various time points throughout the trajectory during vision only and somatosensory feedback conditions along azimuth (x).

Table 4.2: Statistical output of mean position at specific kinematic markers during limb trajectory along azimuth

Outcome Measure	*Viewing Eye*	*Modality*	*Interaction*
100 ms before PV	**F(2,26)=5.81, p=0.0082)**	(F(1,14)=0.01, p=0.9227)	(F(2,26)=2.73 p=0.0840)
50 ms before PV	**F(2,26)=10.74, p=0.0004)**	(F(1,14)=0.57, p=0.4611)	(F(2,26)=1.50, p=0.2410)
Peak Velocity	**F(2,26)=9.05, p=0.0010)**	(F(1,14)=2.48, p=0.1379)	(F(2,26)=0.96, p=0.3961)
50 ms after PV	**F(2,26)=6.05, p=0.0069)**	**(F(1,14)=4.68, p=0.0484)**	(F(2,26)=1.21, p=0.3136)
100 ms after PV	**F(2,26)=3.69, p=0.0389)**	**(F(1,14)=6.08, p=0.0272)**	(F(2,26)=1.65, p=0.2117)
Peak Deceleration	F(2,26)=2.57, p=0.0959)	(F(1,14)=3.77, p=0.0727)	(F(2,26)=1.34, p=0.2794)
End	F(2,26)=0.72, p=0.4969)	(F(1,14)=2.60, p=0.1291)	(F(2,26)=1.35, p=0.2770)

Spatial Variability along Azimuth

The spatial variability of the limb position along each time point in the trajectory did not show a main effect of viewing eye or modality. There was also no significant interaction between viewing eye and modality.

Limb Position along Depth

There was no main effect of viewing eye or modality shown for mean limb position at each time point in the trajectory. In contrast to our hypothesis, no interaction was found between viewing eye and modality for mean limb position.

Spatial Variability Along Depth

There was no main effect of viewing eye, or modality for limb position variability along the trajectory in depth. In contrast to our hypothesis, the interaction between viewing eye and modality showed no significant effect for spatial limb variability along depth

4.4 Discussion

Study 2 addressed the potential limitations of study 1: effects of practice and visibility of the limb holding the needle. Our first hypothesis was that placement time would be reduced when somatosensory feedback was provided under monocular viewing conditions. This hypothesis was somewhat supported, as the results showed shorter placement time when somatosensory input was provided regardless of viewing condition. To further investigate the effect of placement time findings, kinematic measures associated with motor planning and execution were examined. In accordance with our second hypothesis, the finding of higher peak acceleration provides evidence that somatosensory input contributed to motor planning. Results also provide some support for our third hypothesis as straighter limb trajectory (i.e., less deviation along azimuth) was found across all viewing conditions when somatosensory input was available in comparison to the vision only condition. Overall, somatosensory input provided performance benefits in comparison to the vision only condition, which was most evident during the final stage of movement as the bead was placed onto the needle.

Comparison of Findings Between the Two Studies

In general, the findings between the two studies were very similar. However, two major differences were shown with respect to placement time and peak acceleration measures. These findings may be attributed to practice and visibility of the limb providing somatosensory feedback.

Adding practice trials had two effects on the performance of the placement task. First, there was an overall reduction in the placement duration across all the experimental conditions. Specifically, placement duration was ~ 1000 ms in study 1, and ~700 ms in study 2. Second, the magnitude of the somatosensory effect on placement time was larger during monocular viewing in study 1. Specifically, placement time was ~170 ms shorter with somatosensory input during monocular viewing in study 1, and in study 2 the improvement was less than 70 ms. Importantly, the improvement was similar during monocular and binocular viewing. These findings indicate that when participants are given the opportunity to practice, they become more proficient with task performance, and more specifically, with using additional sensory input. (Elliot et al., 2004). Practice can potentially influence the various processing stages of goal-directed movements: target localization, motor planning, and movement execution (Figure 1.1). Within our study it was hypothesized that somatosensory input identifying target location would facilitate movement planning. This finding was evident in study 2 as peak acceleration was higher when somatosensory input was provided. When comparing the findings from study 1 with that of study 2, peak accelerations were ~1000mm/s^2 higher in study 2. Previous literature has shown that benefits in movement occur through changes in the underlying processes of motor planning and programming when practice is provided (van Mier, Hulstijn & Petersen, 1993). It is possible that practice allows for increased automaticity in the analysis of information provided from visual and somatosensory modalities (stimulus identification and localization) during motor planning. Practice may also improve the response selection stage, thus creating a more effective motor program/efference copy to simulate the movement (Schmidt & Lee, 2014). As previously discussed, transforming the signal from one coordinate frame to another during motor planning can cause errors in mapping the target location, or in computation (Sober et al., 2003). Thus, it is possible that the CNS requires practice, or ‘training’ in order to reduce errors in transformation. Although these underlying processes are not directly observable, measures such as peak acceleration can provide insight as to how practice may lead to a more effective performance by improving aspects of motor planning.

Our second manipulation, that is visibility of the limb providing somatosensory input, may have also affected placement time and peak acceleration. Since practice and limb visibility were manipulated at the same time within our study, it is difficult to disentangle the effects of practice and limb visibility on our findings directly. In order to gain a better understanding, a future study should examine practice under conditions where visual input of the limb is present, and absent. This study would then provide insight as to whether having visibility of the limb is critical for target localization.

In conclusion, study two addressed to major limitations of study one: practice effects and lack of visibility of the limb providing somatosensory feedback. Overall, the results for both studies provide evidence that somatosensory feedback about target location facilitates the performance of a high precision placement task. Even a short amount of practice significantly improves performance across all viewing conditions.

Section 5

5.1 General Discussion

Normal binocular vision provides an advantage during the performance of everyday goal-directed movements (Melmoth et al., 2006). When binocular vision is disrupted or absent, the input from another modality may provide important information for performing tasks of everyday living. Within our two studies, the contribution of somatosensory input towards target localization was examined to identify the task conditions where somatosensory input improves placement time performance.

Our study provides insight into the contribution of somatosensory input towards 3D target localization. Overall performance measures were faster in study two compared to that of study one. More specifically, placement time during monocular viewing with somatosensory feedback in study 2 was similar to the placement time found during binocular viewing in study 1 (~0.750s). Although only 5 standardized practice trials were provided within each viewing condition, the results clearly demonstrate the improvement in task performance occurs with practice. Determining the amount of practice required for optimal performance is difficult as multiple factors may play a role. For example, some participants may have better hand-eye coordination and require less practice. Extended periods of practice may also cause attentional deficits, or fatigue which in turn could negatively affect performance on the bead-threading task. Although it is difficult to determine how much practice is required, it is evident that standardized practice can improve overall performance during this complex task.

The experimental trials with and without somatosensory feedback in both studies were randomized. Previous literature has demonstrated that random practice leads to better performance during retention/transfer tests compared to that of blocked practice (Shea & Morgan., 1979; Magill & Hall., 1990). Random practice may be more beneficial in motor learning as it forces the participant to engage in active learning, thus preventing repetitive movements, or through creating a new solution to complete the task on each trial (Schmidt & Lee, 2014). More specifically, random practice would require the participant to reconstruct a new action plan before executing the movement that corresponds to the current trial. Whereas with blocked practice, the action plan for the upcoming trial would still be active in working memory from the preceding trial (Lee & Magill., 1983; Lee, Magill, & Weeks, 1985). Therefore, having randomized practice may require more cognitive effort, which in turn may be a critical factor leading to improved task performance.

5.2 Future Directions & Limitations

There are some implications from this research that can be used for future studies. First, the results indicate that somatosensory input helps contribute to placement time under binocular and monocular conditions. Our study focused on examining how the kinematics of the reaching movement contribute to this effect, however, due to the time constraints the eye movement data were not fully analyzed. There are two important analyses that could provide further insight into the contribution of somatosensory input to task performance: fixation stability and temporal hand-eye coordination. The results from this study showed that when viewing monocularly, visual information is less reliable, thus a longer fixation on the target was required in order to perform the task successfully. There was no evidence that somatosensory input affects fixation duration; however, it is possible that fixation stability was better with the additional feedback, which could be associated with improvements in bead placement performance. Therefore, examining fixation stability may provide insight as to how somatosensory input directly improves performance under monocular viewing conditions. Secondly, examining hand-eye coordination could provide further insight on how somatosensory input is used for placement. Previous literature has shown that when viewing monocularly, the temporal coordination between the eyes and the hand during the place-to-reach transition phase becomes disrupted (Gonzalez & Niechwiej-Szwedo, 2016). Thus, examining temporal hand eye coordination may provide insight into how additional somatosensory input affects hand-eye coordination during monocular viewing.

This research study does have some limitations that should be addressed in future research. First, our statistical approach for evaluating the changes along the limb trajectory used multiple comparisons, which creates a risk for type I error. The method of comparing multiple time points along the trajectory can cause potential false positives; therefore another statistical approach that accounts for the time effect may be a better method. Another method of analysis that should be considered for future reference is waveform analysis, as this new technique observes the trajectory as a whole time series.

Our second limitation was only examining a healthy population. All participants were University students with no visual impairment, thus, the results from this study may not necessarily generalize to those with have visual impairments. The mean age of participants was 24 years, therefore, this study may not generalize to older or younger population as previous studies have shown that combining input from multiple modalities does differ based on development (Gori, Del Viva, Sandini, & Burr, 2008; Gori, Sandini, & Burr, 2012; Nardini, et al., 2013).

5.3 Final Conclusion

This thesis demonstrates that information from another modality can improve planning and execution of a high precision reach-to-place task under certain conditions. Practice trials are a critical component leading to improved performance. Importantly, despite the improved performance during monocular viewing with somatosensory input, performance did not reach the same level that was found during binocular viewing. Overall, these studies provide insight towards conditions that should be considered when developing new training regimens for individual with abnormal binocular vision.

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Appendices

Appendix A

Table A1: Study One-Percentages of Trials used per Participant for Eye Position Data Analysis

Subject	Binocular Trials	Monocular Trials	Total	% of Trials Not Used
1	1	1	2	6%
2	0	4	4	13%
3	2	6	8	26%
4	1	4	5	16%
5	0	3	3	10%
6	1	7	8	26%
7	1	3	4	13%
8	1	14	15	50%
9	5	9	14	46%
10	2	4	6	20%
11	0	4	4	13%
12	10	18	28	93%
13	0	0	0	0%
14	0	0	0	0%
15	0	2	2	6%

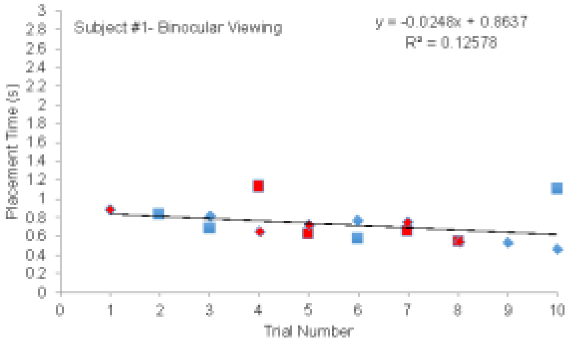
Table A2: Study One-Number of Trials Excluded from Kinematic Analysis

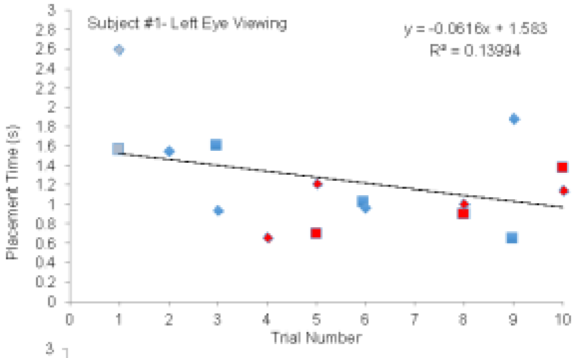
Subject	# of Dropped Beads Binocular Viewing	# of Dropped Beads (Monocular Right Eye)	# of Dropped Beads (Monocular Left Eye)	# of Lost Tracking /Collection Error Trials
1	1	0	0	0
2	0	0	0	1
3	0	1	1	0
4	0	0	0	1
5	0	0	0	2
6	0	0	0	5
7	0	0	0	0
8	0	0	1	0
9	0	0	1	1
10	0	0	0	1
11	1	0	1	0
12	0	2	1	0
13	0	0	2	0
14	0	0	1	0
15	1	1	2	1

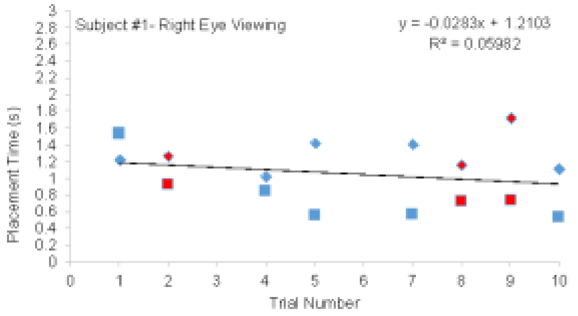
Table A3: Study One-Skewness & Kurtosis Values for Each Outcome Measures

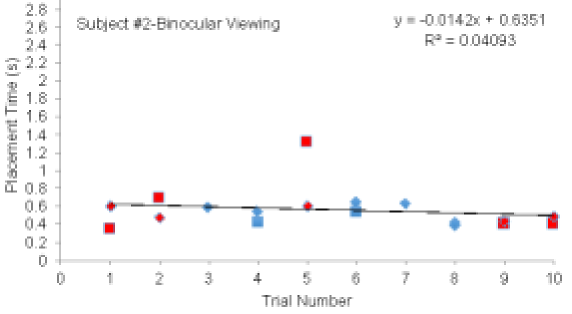
Measure	Skewness Before	Skewness After	Kurtosis Before	Kurtosis After
PT	1.524	0.736	3.506	0.092
PV	-0.736	-0.759	0.497	0.528
MT	0.730	0.596	0.509	-0.092
PA	-1.034	-1.034	1.241	1.236
PAx	1.403	1.351	3.953	2.804
PAz	1.531	1.497	2.581	2.468
PVb100x	0.837	0.815	1.669	1.531
PVb100z	0.849	0.738	0.725	0.296
PVb50x	0.497	0.503	0.645	0.607
PVb50z	0.319	0.224	0.807	0.526
PVx	0.302	0.329	0.320	0.297
PVz	-0.432	-0.477	1.759	1.593
PVa50x	0.194	0.224	0.119	0.104
PVa50z	-0.765	-0.731	2.503	2.310
PVa100x	0.208	0.230	0.077	0.073
PVa100z	-0.800	-0.726	3.00	2.736
PDx	0.251	0.275	0.045	0.036
PDz	-0.595	-0.517	2.11	1.894
Endx	0.402	0.406	0.010	0.008
Endz	-0.828	-0.756	3.630	3.445

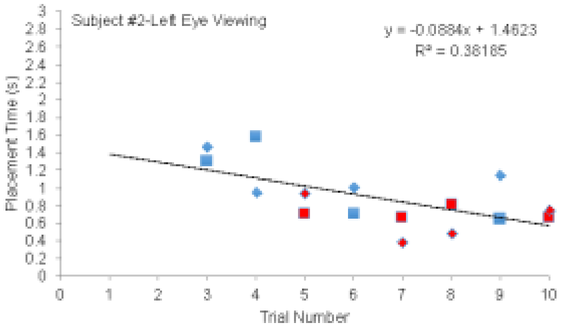
Appendix B: Study One-Placement Time Trials One to Ten per Subject and Viewing Condition

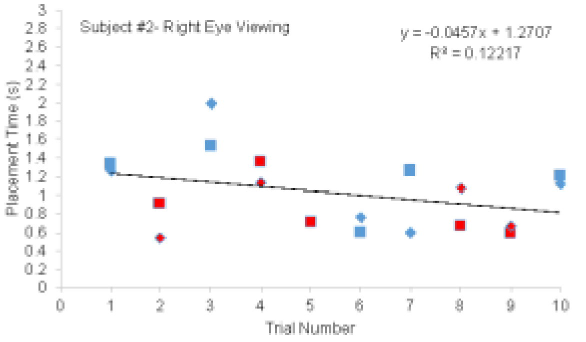


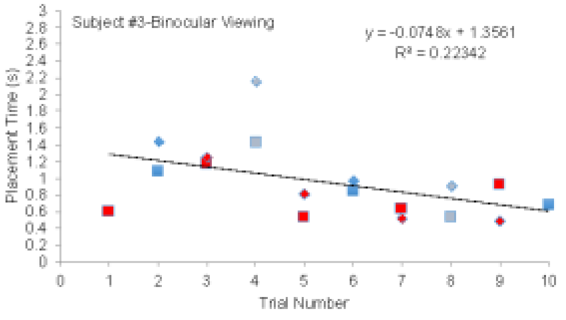


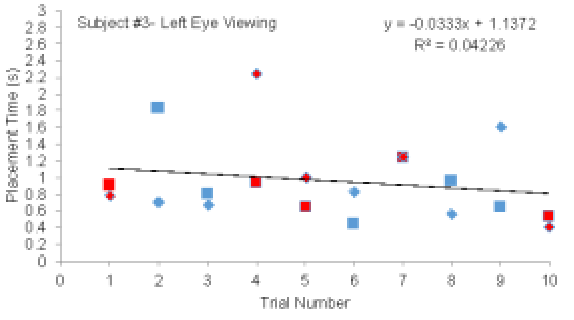




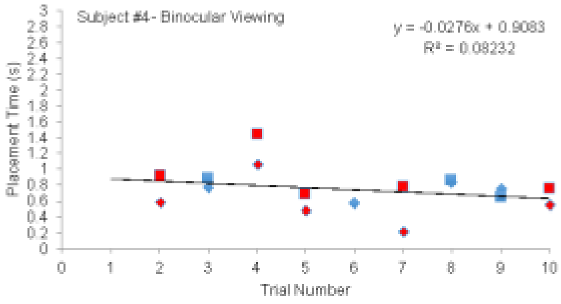


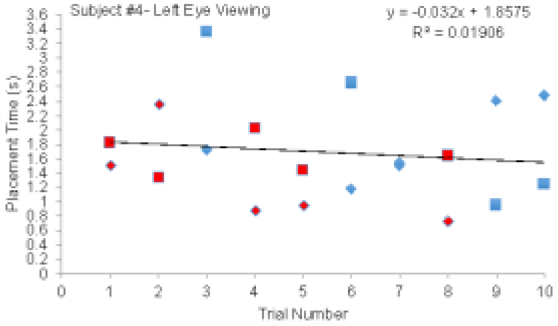


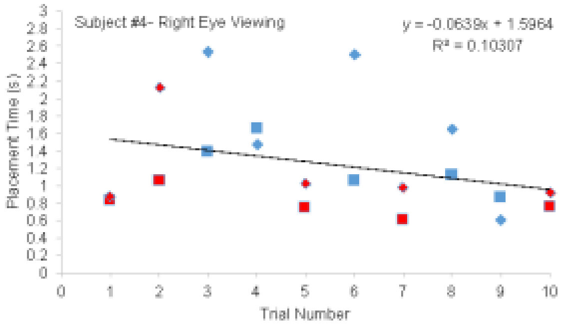


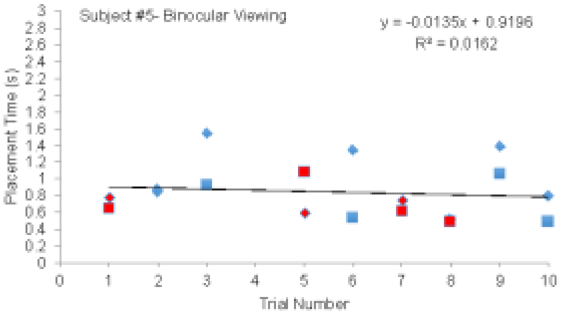


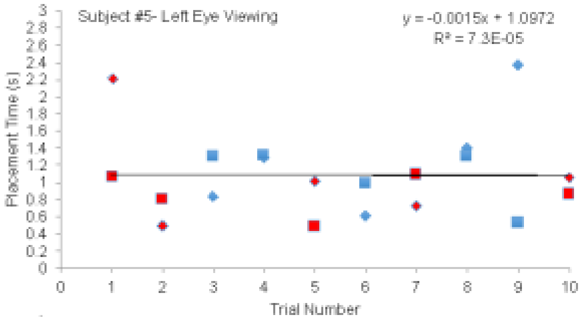

Subject #3 -Right Eye Viewing
y = 0.0264x + 0.5727
R² = 0.04455
Placement Time (s)
Trial Number

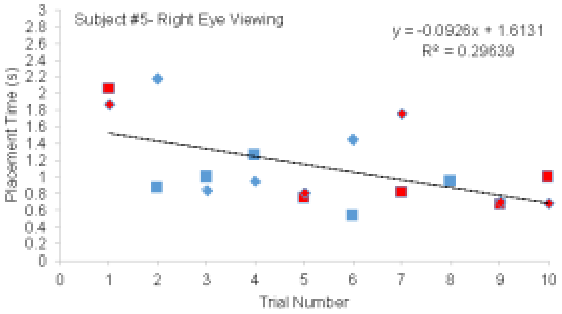

Subject #4- Binocular Viewing
y = -0.0276x + 0.9083
R² = 0.08232
Placement Time (s)
Trial Number

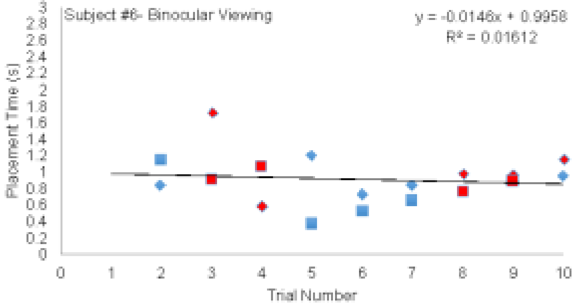

Subject #4- Left Eye Viewing
y = -0.032x + 1.8575
R² = 0.01906
Placement Time (s)
Trial Number

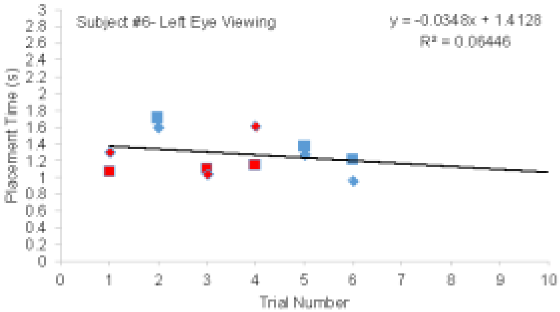

Subject #4- Right Eye Viewing
y = -0.0639x + 1.5964
R² = 0.10307
Placement Time (s)
Trial Number


Subject #5- Binocular Viewing
y = -0.0135x + 0.9196
R² = 0.0162
Placement Time (s)
Trial Number


Subject #5- Left Eye Viewing
y = -0.0015x + 1.0972
R² = 7.3E-05
Placement Time (s)
Trial Number


Subject #5- Right Eye Viewing
y = -0.0926x + 1.6131
R² = 0.29639
Placement Time (s)
Trial Number


Subject #6- Binocular Viewing
y = -0.0146x + 0.9958
R² = 0.01612
Placement Time (s)
Trial Number


Subject #6- Left Eye Viewing
y = -0.0348x + 1.4128
R² = 0.06446
Placement Time (s)
Trial Number
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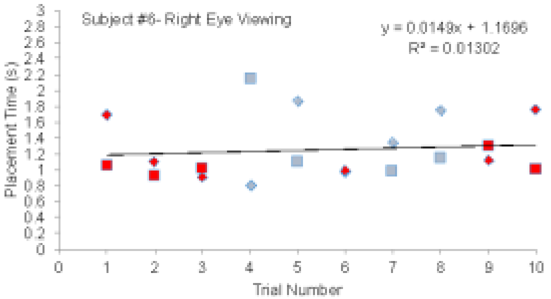
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
0
1
2
3
4
5
6
7
8
9
10


Subject #6- Right Eye Viewing
y = 0.0149x + 1.1696
R² = 0.01302
Placement Time (s)
Trial Number
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0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
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3
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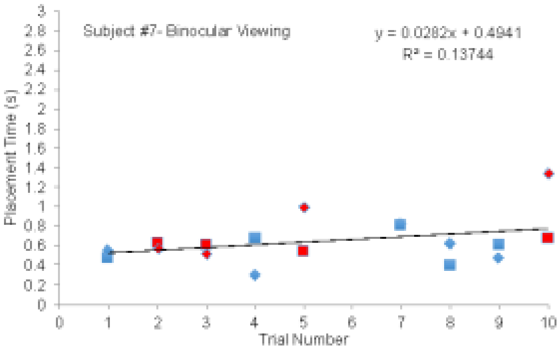
Subject #7- Binocular Viewing
y = 0.0282x + 0.4941
R² = 0.13744
Placement Time (s)
Trial Number
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0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
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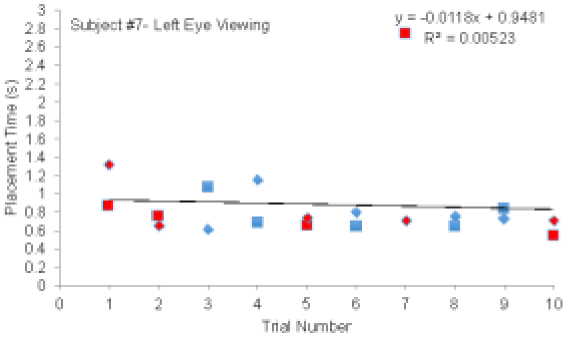
Subject #7- Left Eye Viewing
y = -0.0118x + 0.9481
R² = 0.00523
Placement Time (s)
Trial Number
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0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
0
1
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4
5
6
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Subject #7- Right Eye Viewing
y = 0.0049x + 1.0613
R² = 0.00051
Placement Time (s)
Trial Number
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
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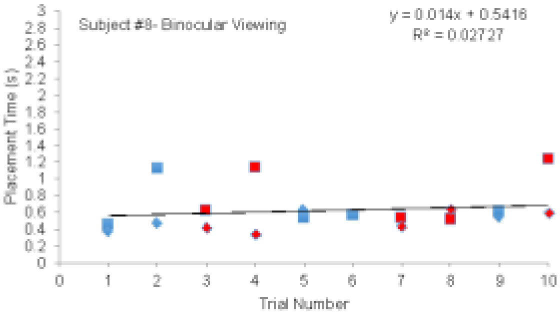
Subject #8- Binocular Viewing
y = 0.014x + 0.5416
R² = 0.02727
Placement Time (s)
Trial Number
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0.6
0.8
1
1.2
1.4
1.6
1.8
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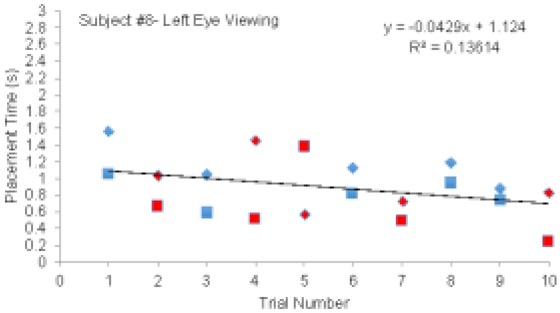
Subject #8- Left Eye Viewing
y = -0.0429x + 1.124
R² = 0.13614
Placement Time (s)
Trial Number
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0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
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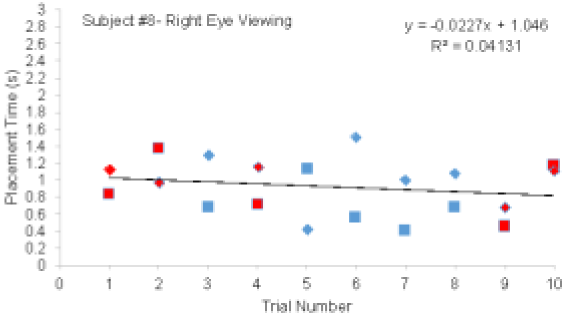
Subject #8- Right Eye Viewing
y = -0.0227x + 1.046
R² = 0.04131
Placement Time (s)
Trial Number
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0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
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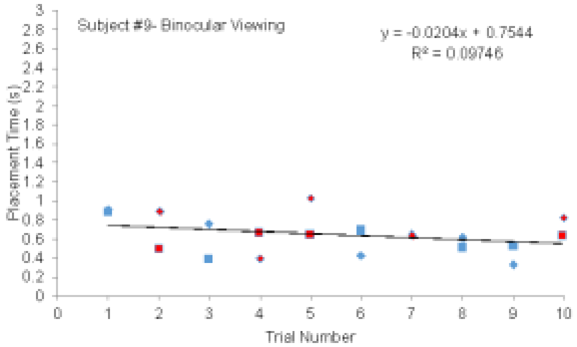
Subject #9- Binocular Viewing
y = -0.0204x + 0.7544
R² = 0.09746
Placement Time (s)
Trial Number
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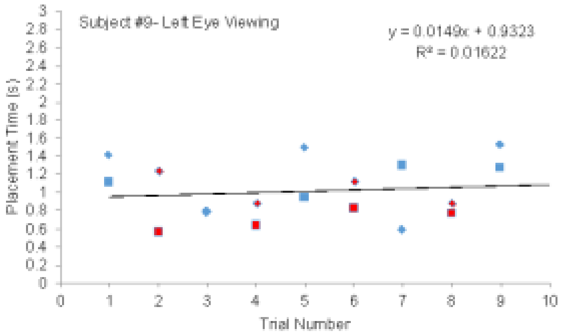
0 1 2 3 4 5 6 7 8 9 10


Subject #9- Left Eye Viewing
y = 0.0149x + 0.9323
R² = 0.01622
Placement Time (s)
Trial Number
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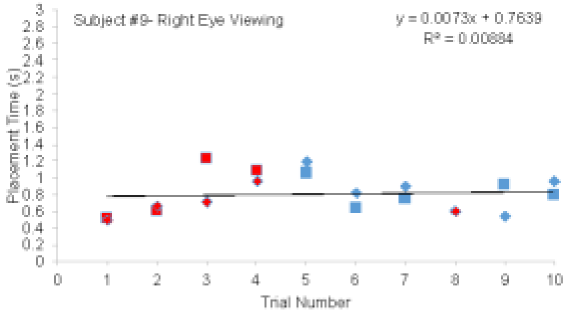
0 1 2 3 4 5 6 7 8 9 10


Subject #9- Right Eye Viewing
y = 0.0073x + 0.7639
R² = 0.00884
Placement Time (s)
Trial Number
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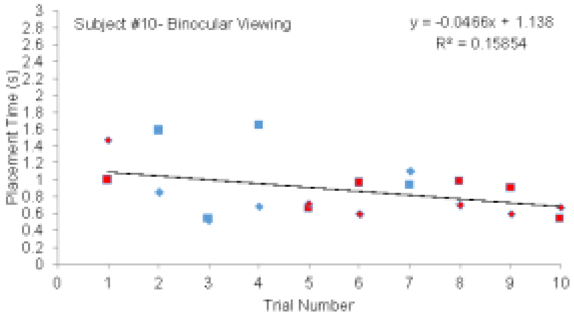
Subject #10- Binocular Viewing
y = -0.0466x + 1.138
R² = 0.15854
Placement Time (s)
Trial Number
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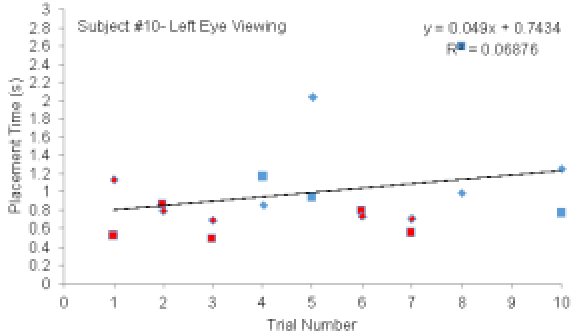
0 1 2 3 4 5 6 7 8 9 10


Subject #10- Left Eye Viewing
y = 0.049x + 0.7434
R² = 0.06876
Placement Time (s)
Trial Number
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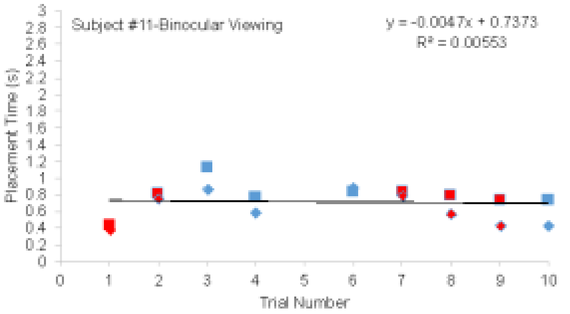
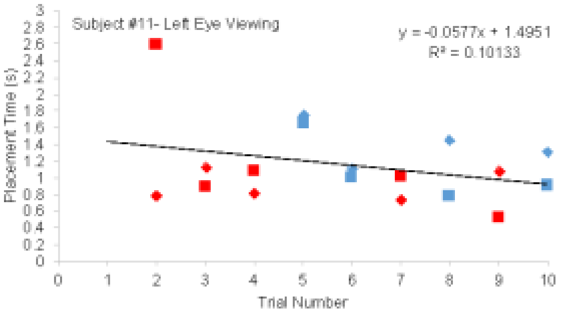
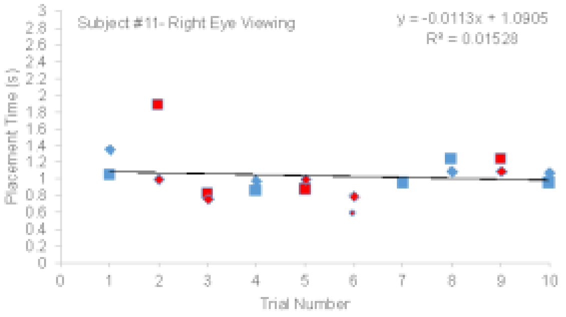
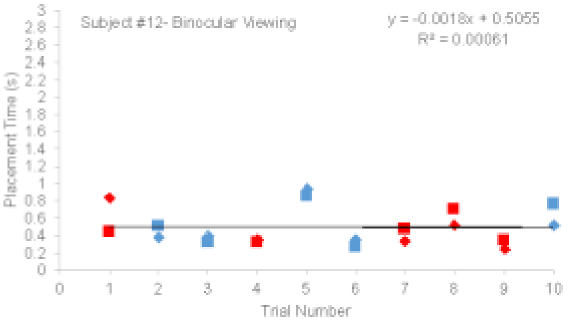
0 1 2 3 4 5 6 7 8 9 10

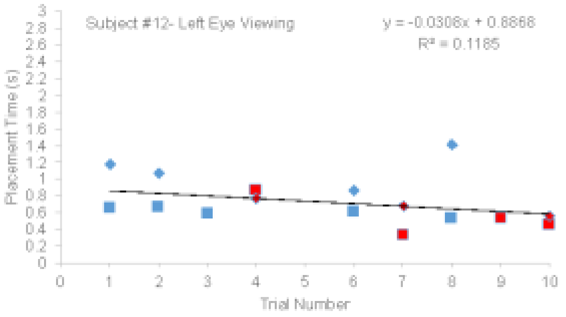

Subject #10- Right Eye Viewing
y = -0.0204x + 1.178
R² = 0.0277
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

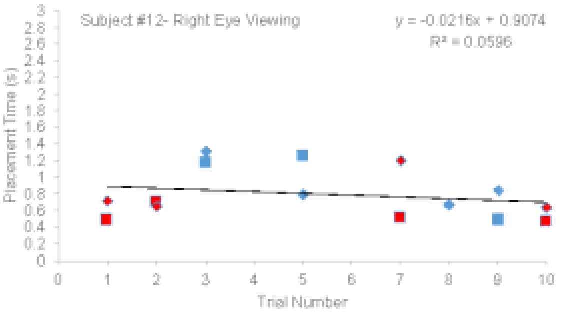

Subject #11-Binocular Viewing
y = -0.0047x + 0.7373
R² = 0.00553
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

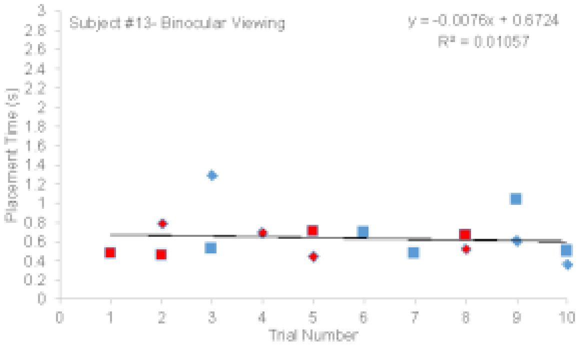

Subject #11- Left Eye Viewing
y = -0.0577x + 1.4951
R² = 0.10133
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

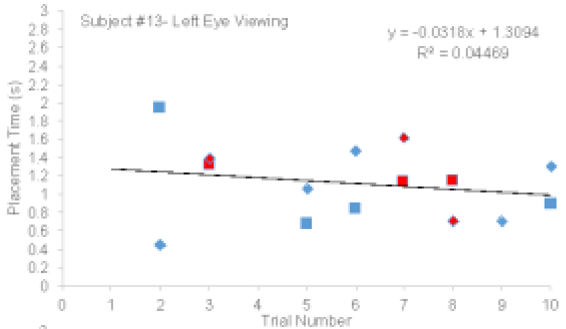

Subject #11- Right Eye Viewing
y = -0.0113x + 1.0905
R² = 0.01528
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

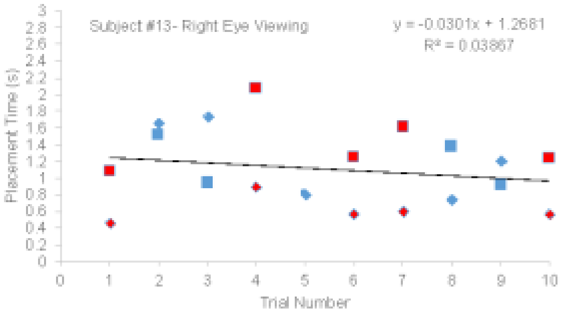

Subject #12- Binocular Viewing
y = -0.0018x + 0.5055
R² = 0.00061
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

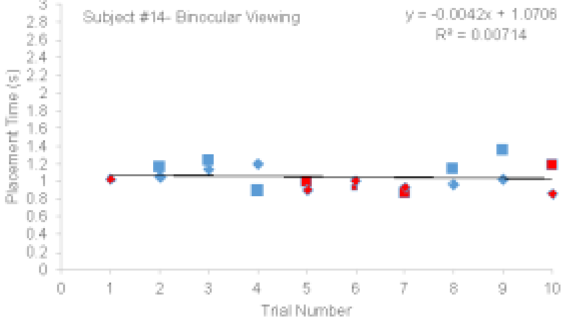

Subject #12- Left Eye Viewing
y = -0.0308x + 0.8868
R² = 0.1185
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

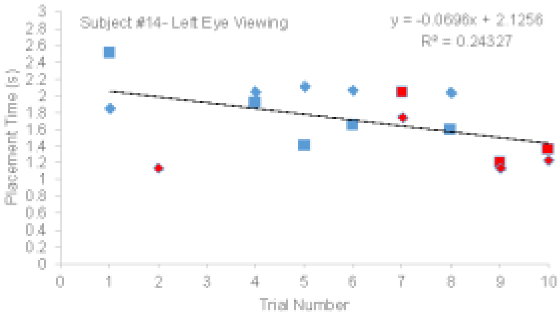

Subject #12- Right Eye Viewing
y = -0.0216x + 0.9074
R² = 0.0596
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

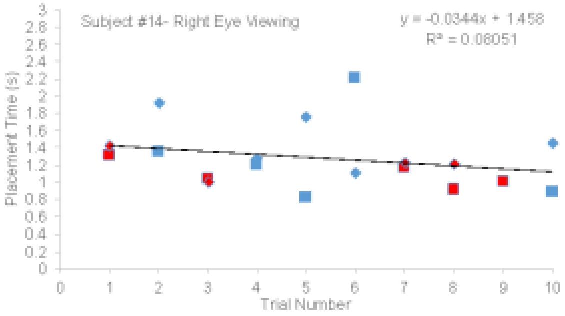

Subject #13- Binocular Viewing
y = -0.0076x + 0.6724
R² = 0.01057
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

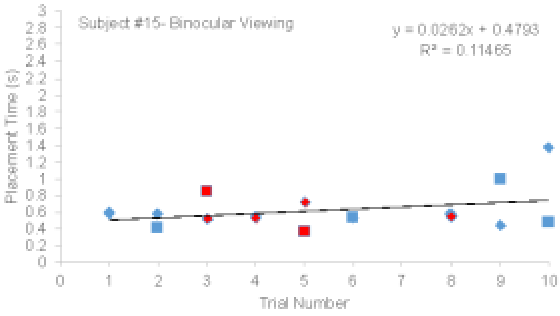

Subject #13- Left Eye Viewing
y = -0.0318x + 1.3094
R² = 0.04469
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

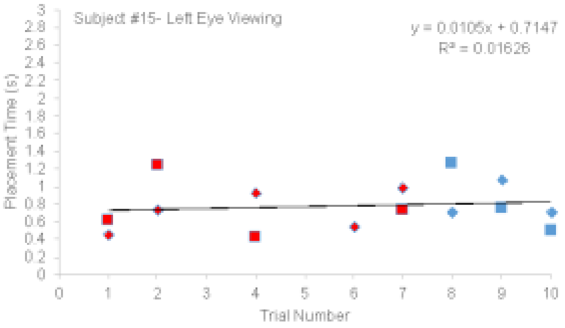

Subject #13- Right Eye Viewing
y = -0.0301x + 1.2681
R² = 0.03867
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

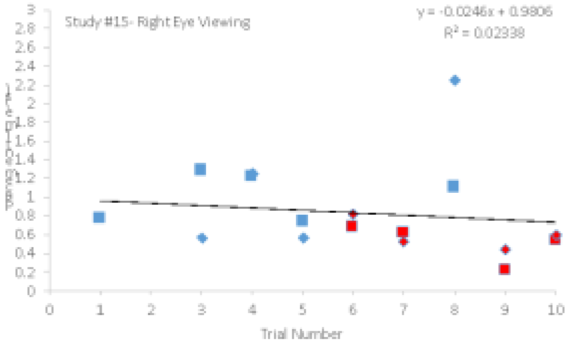

Subject #14- Binocular Viewing
y = -0.0042x + 1.0706
R² = 0.00714
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10


Subject #14- Left Eye Viewing
y = -0.0698x + 2.1256
R² = 0.24327
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number


Subject #14- Right Eye Viewing
y = -0.0344x + 1.458
R² = 0.08051
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

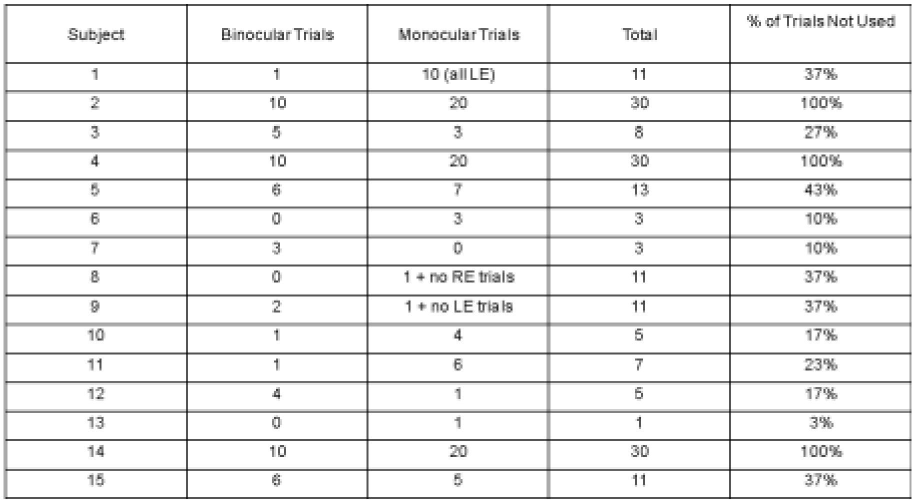

Subject #15- Binocular Viewing
y = 0.0262x + 0.4793
R² = 0.11465
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number


Subject #15- Left Eye Viewing
y = 0.0105x + 0.7147
R² = 0.01626
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number


Study #15- Right Eye Viewing
y = -0.0246x + 0.9806
R² = 0.02338
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

Appendix C

Table C1: Study Two-Percentages of Trials used per Participant for Eye Position Data Analysis



Subject	Binocular Trials	Monocular Trials	Total	% of Trials Not Used
1	1	10 (all LE)	11	37%
2	10	20	30	100%
3	5	3	8	27%
4	10	20	30	100%
5	6	7	13	43%
6	0	3	3	10%
7	3	0	3	10%
8	0	1 + no RE trials	11	37%
9	2	1 + no LE trials	11	37%
10	1	4	5	17%
11	1	6	7	23%
12	4	1	5	17%
13	0	1	1	3%
14	10	20	30	100%
15	6	5	11	37%

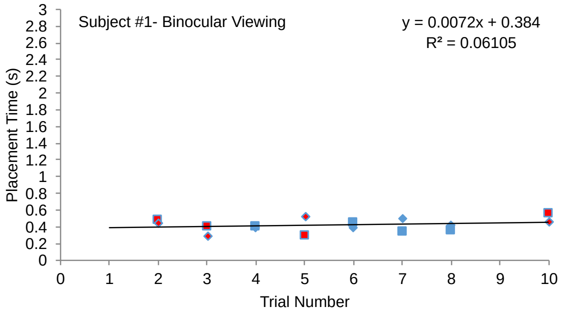
Table C2: Study Two-Number of Trials Excluded from Kinematic Analysis

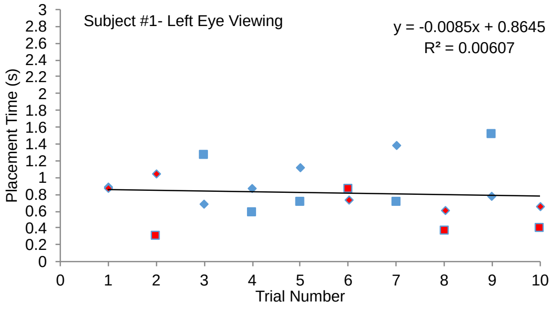
Subject	# of Dropped Bead Binocular Viewing	# of Dropped Beads (Monocular Right Eye)	# of Dropped Beads (Monocular Left Eye)	# of Lost Tracking/Collection Error Trials
1	2	0	0	4
2	1	0	0	0
3	0	1	0	0
4	0	1	0	0
5	0	0	1	1
6	0	0	1	0
7	0	0	0	1
8	0	0	0	0
9	0	0	0	No RE
10	0	0	0	No LE & 1 RE
11	0	0	1	1
12	0	0	1	0
13	0	0	1	1
14	0	0	0	0
15	0	2	1	1

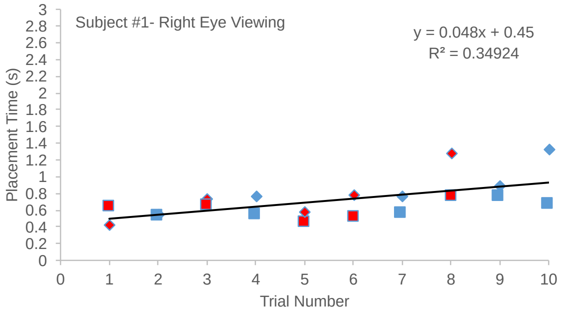
Table C3: Study Two-Skewness & Kurtosis Values for Each Outcome Measures

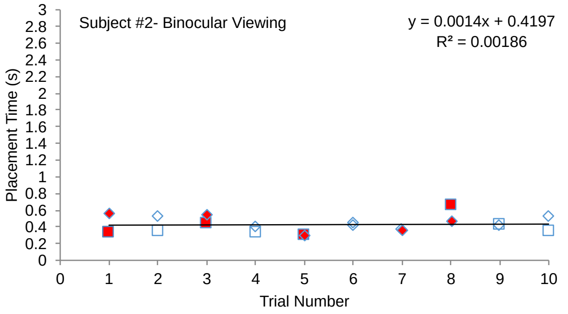
Measure	Skewness Before	Skewness After	Kurtosis Before	Kurtosis After
PT	1.338	1.00	2.759	0.987
PV	-0.363	-1.580	11.88	3.637
MT	0.581	0.501	0.674	0.199
PA	-1.567	-1.580	3.499	3.512
PAx	0.728	0.748	3.539	3.573
PAz	2.440	2.430	8.997	9.140
PVb100x	0.457	0.663	1.587	1.266
PVb100z	1.672	1.073	5.208	1.455
PVb50x	0.115	0.222	0.428	0.284
PVb50z	1.035	0.492	3.545	1.088
PVx	-0.211	-0.142	0.176	0.024
PVz	-0.133	-0.469	2.487	1.974
PVa50x	-0.330	-0.270	0.327	0.173
PVa50z	-0.659	-0.729	2.605	2.764
PVa100x	-0.325	-0.285	0.372	0.299
PVa100z	-0.879	-0.882	3.262	3.390
PDx	-0.450	-0.422	0.615	0.575
PDz	-0.858	-0.854	2.085	2..139
Endx	-0.308	-0.304	0.735	0.765
Endz	-1.527	-1.471	4.900	4.866

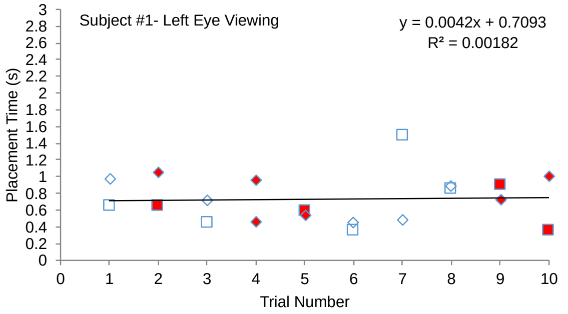
Appendix D: Study Two- Placement Time Trials One to Ten per Subject and Viewing Condition

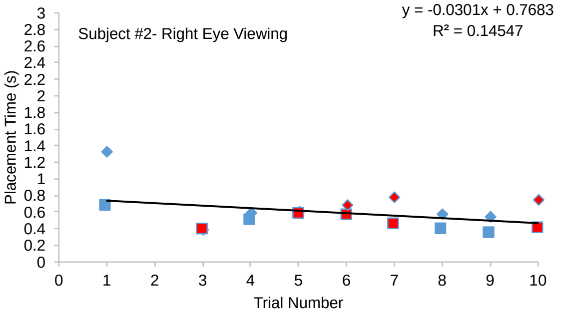


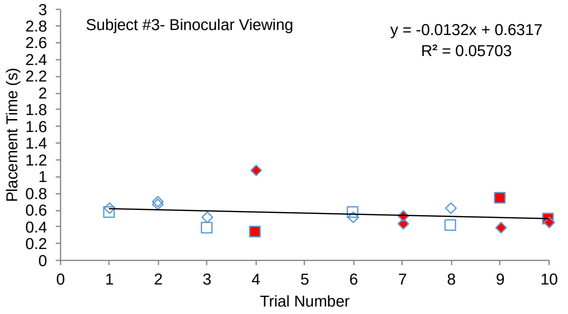


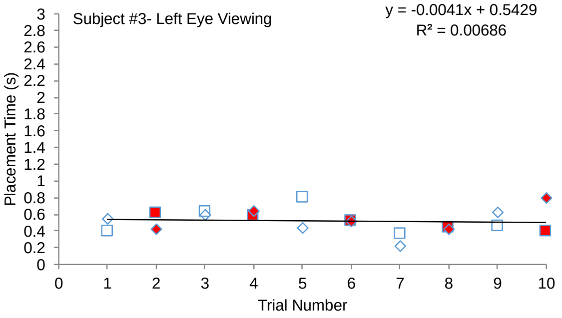


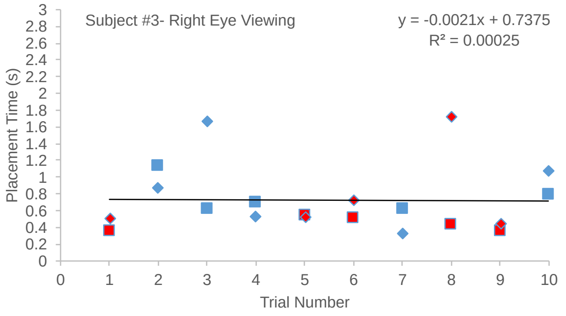


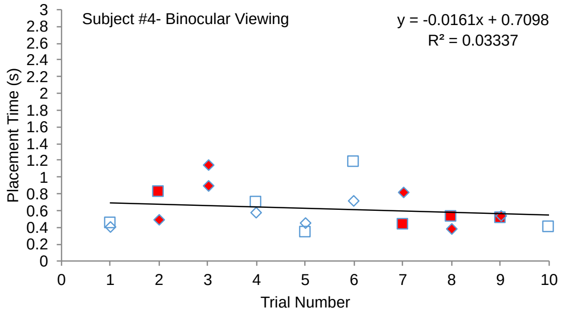


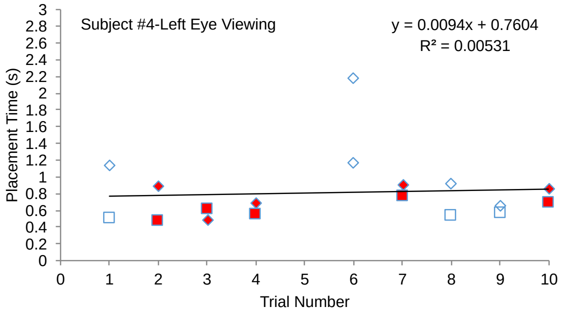


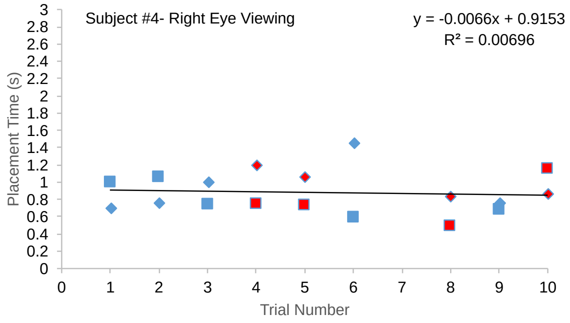


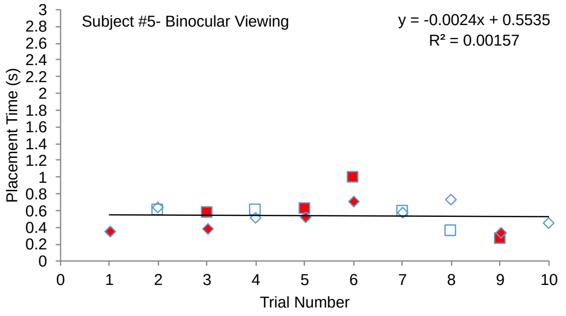


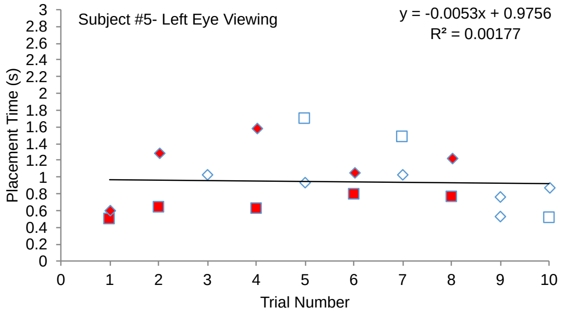

Subject #3- Right Eye Viewing
y = -0.0021x + 0.7375
R² = 0.00025
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

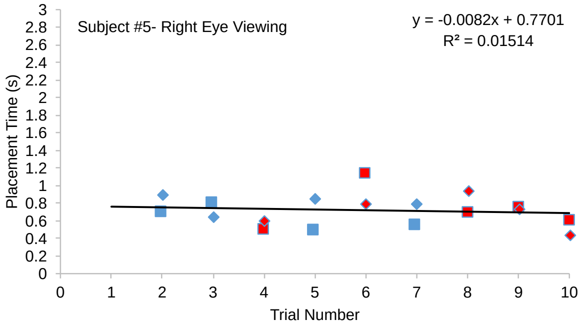

Subject #4- Binocular Viewing
y = -0.0161x + 0.7098
R² = 0.03337
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

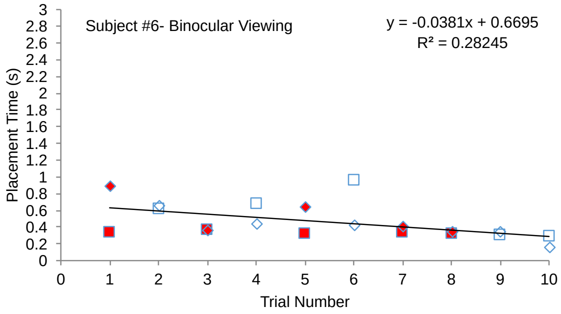

Subject #4-Left Eye Viewing
y = 0.0094x + 0.7604
R² = 0.00531
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

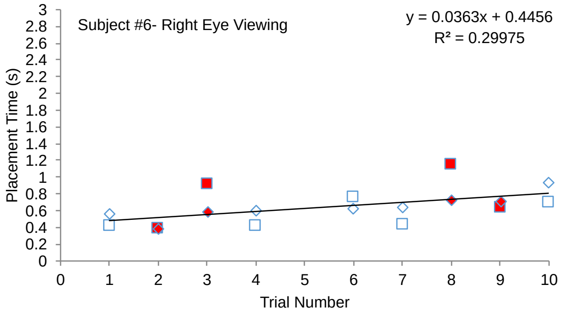

Subject #4- Right Eye Viewing
y = -0.0066x + 0.9153
R² = 0.00696
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

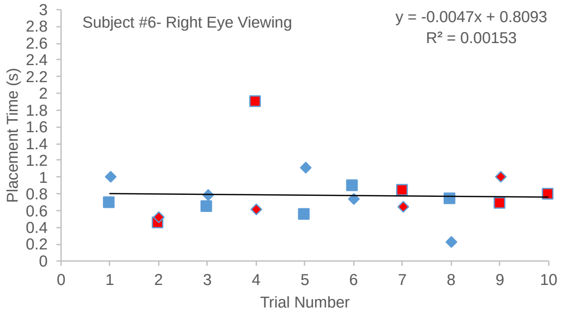

Subject #5- Binocular Viewing
y = -0.0024x + 0.5535
R² = 0.00157
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

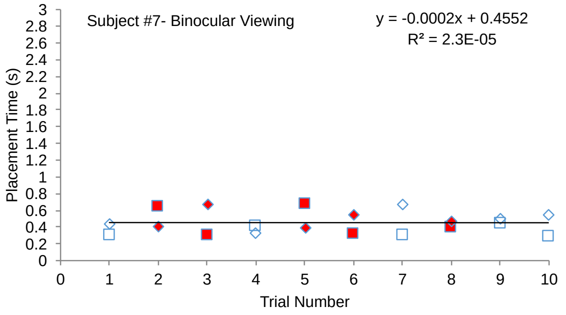

Subject #5- Left Eye Viewing
y = -0.0053x + 0.9756
R² = 0.00177
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

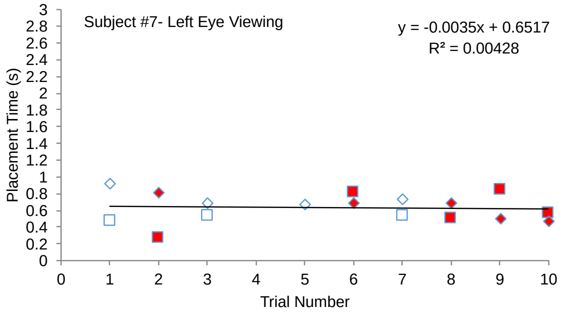

Subject #5- Right Eye Viewing
y = -0.0082x + 0.7701
R² = 0.01514
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

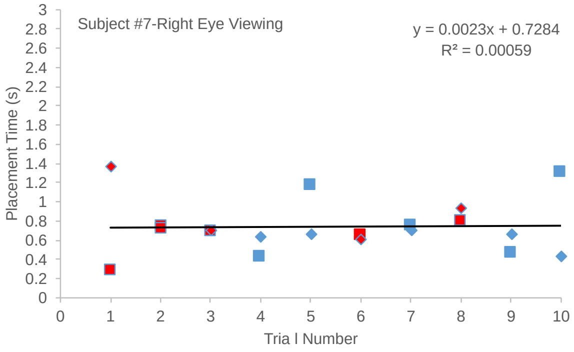

Subject #6- Binocular Viewing
y = -0.0381x + 0.6695
R² = 0.28245
Placement Time (s)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10
Trial Number

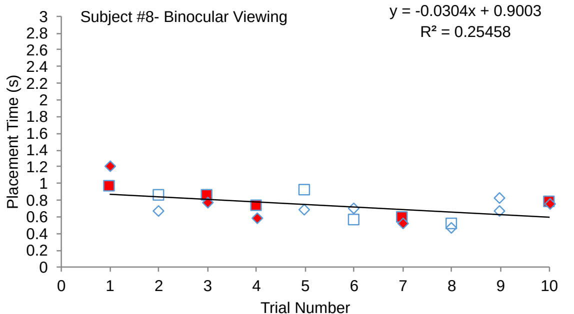

Subject #6- Right Eye Viewing
y = 0.0363x + 0.4456
R² = 0.29975
Placement Time (s)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Trial Number

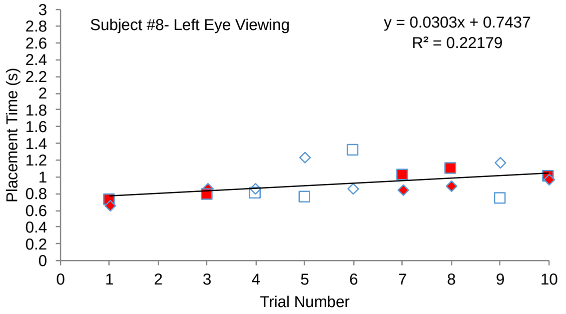

Subject #6- Right Eye Viewing
y = -0.0047x + 0.8093
R² = 0.00153
Placement Time (s)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Trial Number

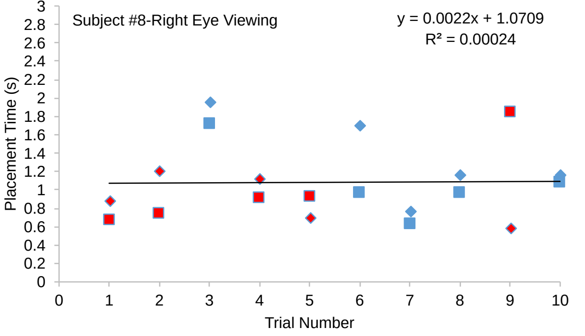

Subject #7- Binocular Viewing
y = -0.0002x + 0.4552
R² = 2.3E-05
Placement Time (s)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Trial Number

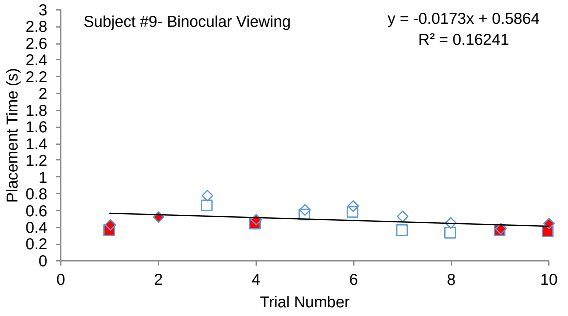

Subject #7- Left Eye Viewing
y = -0.0035x + 0.6517
R² = 0.00428
Placement Time (s)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Trial Number

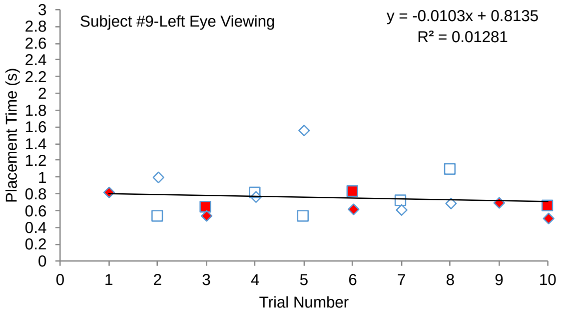

Subject #7-Right Eye Viewing
y = 0.0023x + 0.7284
R² = 0.00059
Placement Time (s)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Tria l Number

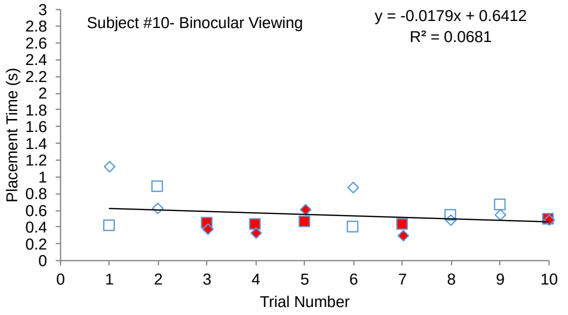

Subject #8- Binocular Viewing
y = -0.0304x + 0.9003
R² = 0.25458
Placement Time (s)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Trial Number

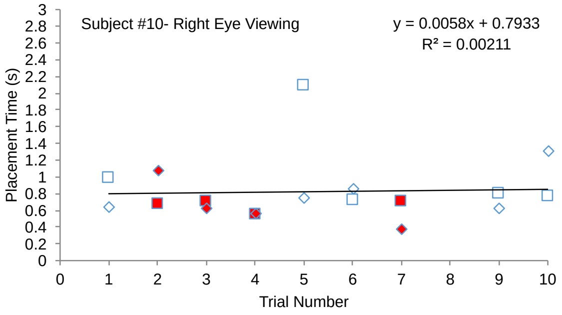

Subject #8- Left Eye Viewing
y = 0.0303x + 0.7437
R² = 0.22179
Placement Time (s)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Trial Number

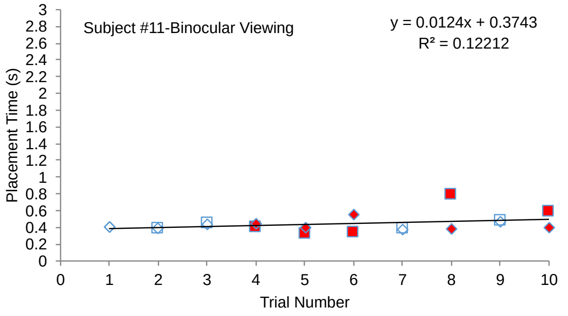

Subject #8-Right Eye Viewing
y = 0.0022x + 1.0709
R² = 0.00024
Placement Time (s)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
Trial Number

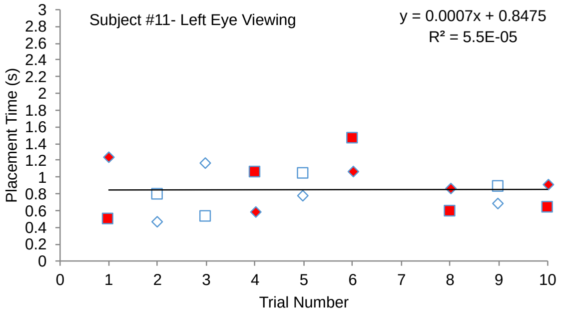

Subject #9- Binocular Viewing
y = -0.0173x + 0.5864
R² = 0.16241
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 2 4 6 8 10

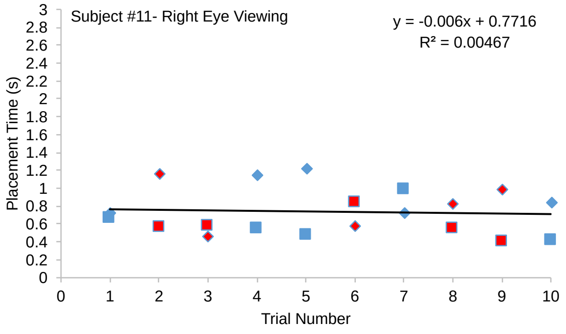

Subject #9-Left Eye Viewing
y = -0.0103x + 0.8135
R² = 0.01281
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

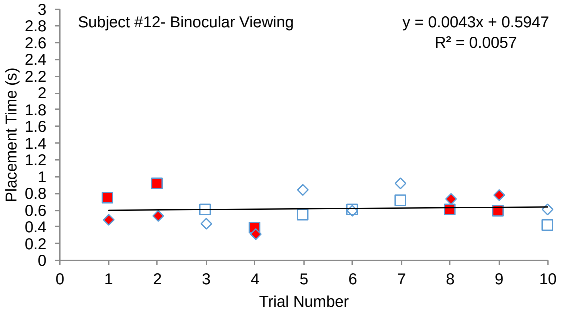

Subject #10- Binocular Viewing
y = -0.0179x + 0.6412
R² = 0.0681
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

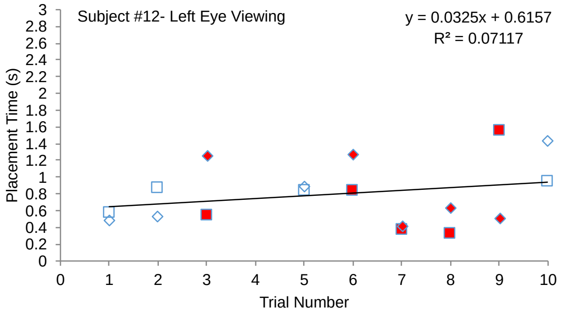

Subject #10- Right Eye Viewing
y = 0.0058x + 0.7933
R² = 0.00211
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

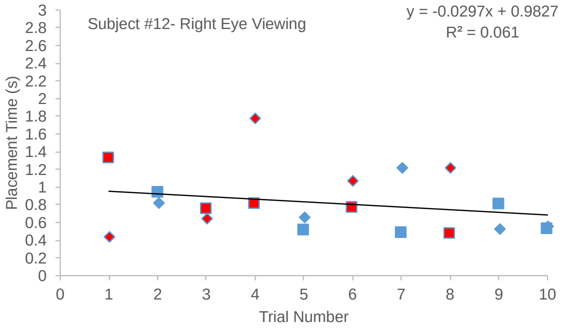

Subject #11-Binocular Viewing
y = 0.0124x + 0.3743
R² = 0.12212
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10

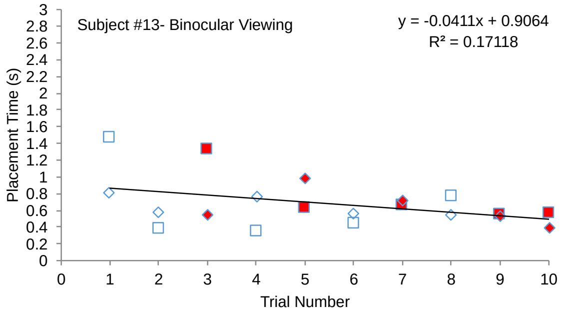

Subject #11- Left Eye Viewing
y = 0.0007x + 0.8475
R² = 5.5E-05
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10


Subject #11- Right Eye Viewing
y = -0.006x + 0.7716
R² = 0.00467
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10


Subject #12- Binocular Viewing
y = 0.0043x + 0.5947
R² = 0.0057
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10


Subject #12- Left Eye Viewing
y = 0.0325x + 0.6157
R² = 0.07117
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10


Subject #12- Right Eye Viewing
y = -0.0297x + 0.9827
R² = 0.061
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10


Subject #13- Binocular Viewing
y = -0.0411x + 0.9064
R² = 0.17118
Placement Time (s)
Trial Number
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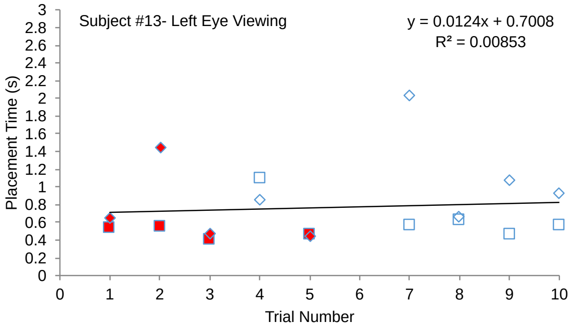
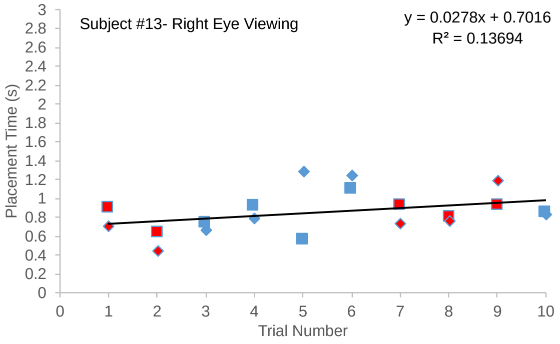
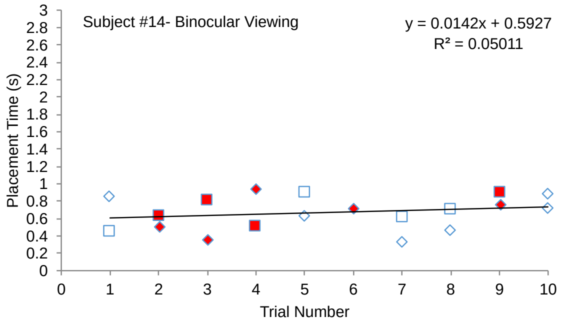
0 1 2 3 4 5 6 7 8 9 10


Subject #13- Left Eye Viewing
y = 0.0124x + 0.7008
R² = 0.00853
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10


Subject #13- Right Eye Viewing
y = 0.0278x + 0.7016
R² = 0.13694
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10


Subject #14- Binocular Viewing
y = 0.0142x + 0.5927
R² = 0.05011
Placement Time (s)
Trial Number
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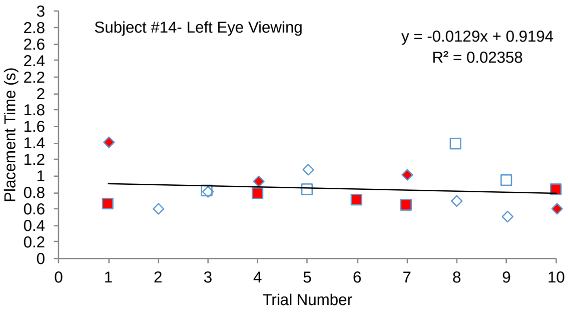
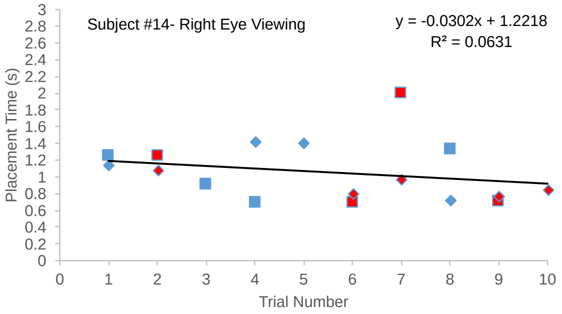
0 1 2 3 4 5 6 7 8 9 10


Subject #14- Left Eye Viewing
y = -0.0129x + 0.9194
R² = 0.02358
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10


Subject #14- Right Eye Viewing
y = -0.0302x + 1.2218
R² = 0.0631
Placement Time (s)
Trial Number
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3
0 1 2 3 4 5 6 7 8 9 10