

The Role of Stereopsis in the Control of Grasp Forces during Prehension

by

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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

Background: Binocular viewing is associated with a superior prehensile performance, which is particularly evident in the latter part of the reach as the hand approaches and makes contact with the target object. However, the visuomotor mechanisms through which binocular vision serves prehensile performance remains unclear. The present study was designed to investigate the role of stereopsis in the planning and control of grasping using outcome measures which reflect predictive control. It was hypothesized that binocular viewing will be associated with more efficient grasp execution because stereoacuity provides more accurate sensory input about the object's material properties to plan appropriate grip forces to successfully lift the target object. In the case when binocular vision is reduced or unavailable, predictive control of grasping will be reduced, and subjects will have to rely on somatosensory feedback to successfully execute the grasp.

Methods: 20 healthy participants (17-35 years, 11 male) with normal vision were recruited. Subjects performed a precision reach-to-grasp task which required them to reach, grasp, and transport a bead (~2 cm in diameter) to a specified location. Subjects were instructed to perform the task as fast as possible in the following viewing conditions: binocular, monocular, and two conditions with reduced stereoacuity: 200 arcsec stereo, 800 arcsec stereo, which were randomized in blocks.

Results: Binocular, compared to monocular viewing had a greater influence on the grasp phase compared to the reach and transport phase. Specifically, there was a 36% increase in post-contact time, 29% decrease in grip force 50ms following object grasp, and 30% increase in grasp errors. In contrast, parameters of the reach and transport phase only demonstrated a 3-8% reduction in performance. Grasp performance was similarly disrupted during binocular viewing with reduced stereoacuity whereby a reduction in stereoacuity was associated with a proportional reduction in grasp performance. Notably, grip force at the time of object lift-off was comparable between all viewing conditions.

Conclusion: The results demonstrate that binocular viewing contributes significantly more to the performance of grasping relative to the reach and transport phase. In addition, the results suggest that stereopsis provides important sensory information which enables the central nervous system to engage in predictive control of grasp forces. When binocular disparity information is reduced or absent, subjects take on a more cautious approach to the grasp and make more errors (i.e., collisions followed by readjustments). Overall, findings from the current study indicate that stereopsis provides important sensory input for the predictive control of grasping, and a progressive reduction in stereopsis is associated with increased uncertainty which results in a greater reliance on somatosensory feedback control.

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List of Abbreviations

AIP – Anterior intraparietal area

Arc sec – Seconds of arc

cGMP – Cyclic guanosine monophosphate

cIPS – Caudal intraparietal area

CNS – Central nervous system

EEG – Electroencephalography

fNIRS – functional near-infrared spectroscopy

GF@LO – Grip force at object lift-off

GF@50 – Grip force 50ms following grasp

IT – Inferior temporal cortex

LIP – Lateral intraparietal area

M1- Primary motor cortex

PP – Posterior parietal area

PPC – Posterior parietal cortex

Stereo – Stereopsis

VIP – Ventral intraparietal area

V1 – Primary visual cortex

3D - Three-dimensional

1.0 Introduction

Our ability to perceive the world in depth is based on many pictorial cues, as well as binocular cues which arise because the eyes are separated horizontally. Depth-perception enables the extraction of crucial information – regarding the object’s location in three-dimensional (3D) space, as well as its physical characteristics and properties – which is important for the execution of many everyday movements. In particular, the performance of fine motor skills, such as prehension (i.e., reaching and grasping) is significantly disrupted when viewing with one eye. Specifically, prehensile movements are slower and contain more corrections and endpoint errors in their trajectory (Melmoth and Grant, 2006; Loftus et al., 2004). These deficits are most pronounced in the final approach phase of a reaching and grasping movement (Watt and Bradshaw, 2002; Melmoth and Grant, 2006). Due to this well-established deficit in prehensile performance when binocular visual input is disrupted, it is thought that a binocular advantage enables superior behavioural performance when compared to monocular vision. It was suggested that binocular advantage arises due to stereopsis, which plays a crucial role in the control of the terminal (or late) phase of the reach. Specifically, it was suggested that stereo-vision provides feedback information (i.e., relative depth) that is critical for the central nervous system (CNS) for making corrections and guiding the hand as it is approaching and grasping the target object (Bradshaw et al., 2002). While the binocular advantage for grasping is well established, several questions remain to be investigated. First, previous studies showed longer duration of grasping using kinematic data (Bradshaw and Elliot, 2003), however, kinetics of grasping have not been examined. Measuring grasp forces will provide additional insight into the role of stereopsis in the control of the grasping movement. Second, most studies examined prehension while viewing was either binocular or monocular, and only one study examined hand kinematics while manipulating

the level of stereoacuity (Melmoth et al., 2009). Finally, the impact of prolonged grasp execution on subsequent movement planning has not been studied in conditions where stereoacuity is progressively disrupted.

To summarize, the present study aimed to investigate the role of stereopsis in the control of the grasp component of prehensile movements. Subjects performed a prehension task that involved reaching, grasping, and transporting objects while stereoacuity was disrupted using convex lenses. The primary objective of this work was to characterize the role of stereopsis on grasp forces. Results from this study provide further understanding of how binocular vision is involved in the control of fine motor skills involving the hands. Understanding the CNS control of upper limb movements is one of the main goals of neuroscience research. In addition, binocular vision is an important visual function, which provides significant advantages in the context of educational performance, social interactions, and overall quality of life (e.g., Smith, Ropar and Allen, 2018; Bardu and Vitelariu, 2016). Therefore, the results from this study may have implications for identifying deficits in binocular vision, which may have functional consequences, as well as the assessment and treatment of individuals with abnormal binocular vision.

The following section first provides a general review of fundamental concepts involving visual processing and binocular vision. The next section provides a comprehensive literature review discussing the current understanding of the influence of binocular vision on prehensile performance.

2.0 Literature Review

2.1 Overview of Visual Processing

Visual processing begins when the light enters the eye. Photons of light from the sun or other artificial sources are reflected from various objects in the surrounding environment and enter the eyeball. These waves of light pass through several translucent tissues of the eye until they reach the light-sensitive photoreceptor cells at the back of the retina. Here, light energy is transduced into a neural signal via a cascade of biochemical events mediated via activation of the cyclic guanosine monophosphate (cGMP) dependent protein kinases. The neural signal is then transmitted from the photoreceptors to bipolar cells, and then to ganglion cells, whose axons form the optic nerve. The optic nerve transmits the signal to the lateral geniculate nucleus (LGN) of the thalamus, and then to the striate cortex (i.e., primary visual cortex, V1) (Wolfe et al., 2015; Kandel et al., 2013).

The retina contains two types of photoreceptors: rods and cones, which respond to different wavelengths. There are three types of cones which respond to different wavelengths, and they are located predominantly at the fovea (i.e., the center of the retina which serves as the point of fixation specialized for seeing details). Consequently, foveal vision provides color vision and the best spatial resolution (i.e., high acuity or sharpness of detail). Rods are activated maximally with 420 nm light stimulus, they are absent at the fovea, and their density is largest at around 20 degrees of eccentricity. Rods are involved in detecting and localizing stimuli that are not directly being focused on (i.e., peripheral vision). Signal processing at the retina involves amplification of object contrast via lateral inhibition. Information transmitted from each eye along the optic nerve decussates at the optic chiasm such that axons carrying input from the nasal retina (temporal visual field) cross to the contralateral side, whereas information from the

temporal retina (nasal visual field) remains ipsilateral. This decussation is the basis of binocular vision because it allows for inputs from both eyes to converge onto binocular cells in V1 (Wolfe et al., 2015; Kandel et al., 2013).

Processes in the striate cortex are considered part of early visual processing. These processes involve extracting basic visual features from the environment, for example V1 cortical neurons respond to bars and lines of various orientations, motion, and color. Importantly, research has shown that neurons in V1 respond to binocular disparity, that is, when the object stimulates non-corresponding retinal locations in each eye (Wolfe et al., 2015; Kandel et al., 2013; Ohzawa et al., 1997). In other words, binocular vision involves processing of visual information from both eyes. The eyes of adult humans are horizontally separated by approximately 6.2 cm. Objects that are fixated (i.e., stimulus falls on the fovea) or that are located in the periphery but fall on the horopter stimulate corresponding retinal points, and they are perceived at the same distance in depth as the fixated object. In contrast, images of objects that fall on non-corresponding retinal points are perceived closer or farther, depending on binocular retinal disparity (Wolfe et al., 2015).

Following the extraction of basic visual features in the scene by early visual processing in the striate cortex, the extrastriate cortex is responsible for processing this information to develop a coherent understanding of the visual environment. Mid-level vision consists of the extrastriate cortex which involves temporal and parietal cortical regions that assemble the local features into groups that can be perceived as objects. Visual processing occurs via two anatomically segregated visual pathways: the ventral and dorsal visual stream, also known as the ‘what’ and ‘where’ visual pathways, respectively. The ventral stream projects from the primary visual cortex, via area V4 to the inferior temporal lobe. This area is involved in processing 2-D and 3-D

shape, color and texture information (Watanabe et al., 2002; Yoshiyama et al., 2004; Inagaki and Fujita, 2016). On the other hand, the dorsal pathway projects to the posterior parietal association cortex which is involved in processing information regarding object's location in space (Uka et al 2000). Additionally, dorsal pathway neurons have been reported to play a role in the neural processing of stereopsis (e.g., Sakata et al., 1997, 1999; Nishada et al., 2001; Nishada, 2004). Specifically, recent neurophysiological studies in alert monkeys have revealed the parietal association cortex plays crucial role in depth perception and visually guided hand movements. For example, a review by Sakata et al. (1997) reported that the dorsal visual pathway is divided into at least two subsystems: inferior regions including V5A, posterior parietal (PP), ventral intraparietal (VIP), and medial temporal (MT) areas for motion vision and superior regions including V6, lateral intraparietal (LIP) and caudal intraparietal (cIPS) areas for coding position and 3D features. Moreover, the authors describe area cIPS as a higher center for stereopsis that integrates various binocular disparity signals (e.g., coding of 3D-orientation and 3D-shape of objects) received from the V3 complex and other extrastriate areas to represent the 3D features. Neurons in area cIPS may send projections to the anterior intraparietal (AIP) area and contribute to the adjustment of the shape and/or orientation of the handgrip for manipulation and grasping of objects (Sakata et al., 1999).

Disparity sensitive neurons are also found in the ventral pathway (Uka et al., 2000; Watanabe et al., 2002; Uka et al., 2005; Yoshiyama et al., 2004; Inagaki and Fujita, 2016). Specifically, inferior temporal cortex (IT) and V4 neurons have disparity selectivity. That is, these neurons changed their response depending on the disparity associated with the visual stimuli. Moreover, disparity-selective neurons were also selective for shape (i.e., most preferred the same type of disparity irrespective of the shape presented). Finally, nearby neurons exhibited

similar disparity selectivity, suggesting the existence of a modular arrangement of neurons for processing of binocular disparity in the IT (Uka et al., 2000). These findings are consistent with reports from Sakata et al. (1999) which proposed that neurons of the AIP area, in the dorsal pathway, may also receive depth cues from the ventral visual pathway to discriminate the 3D shape of the object of manipulation.

2.2 Binocular Advantage for Prehension

Extensive research shows that binocular vision provides a behavioural advantage for prehensile performance (Goodale, 2011; Melmoth and Grant, 2006). Studies that examined the contribution of binocular vision to the control of human prehension typically had subjects perform reaching and grasping movements. In these experiments, objects were cylindrical blocks and visual conditions were randomized, such that viewing was either binocular or monocular (i.e., one eye occluded with an eye patch). Both object size and distance were also commonly manipulated, and subjects were instructed to perform the reach-to-grasp task as quickly and accurately as possible. Upon deconstructing the movement into its individual components, it was found that, when binocular visual information was absent, both planning and execution (i.e., online control) components of the movement were significantly affected (Goodale, 2011; Melmoth and Grant, 2006). These were reflected via proxy measures focussing on the early and late phase of the hand trajectory (e.g., overall movement time, time to peak velocity, and time from peak velocity to object contact). Successive investigations also found similar behavioural results in studies involving patients with binocular vision deficits, such as amblyopia or strabismus, and patients who were enucleated (Buckley et al., 2015; Grant et al., 2014, 2007; Suttle et al., 2011; Goodale, 2011). The remainder of this section will review the current

understanding of how binocular vision contributes to a behavioural advantage, that is, how performing the task with two eyes enables an advantage when compared to performing the task with one eye.

The binocular advantage has been studied previously using a kinematic approach. Studies show that there are several aspects in the prehensile movement that, when evaluated via proxy measures, indicate better and more efficient performance (Goodale, 2011; Melmoth and Grant, 2006). The major finding, consistent across all prehension studies, is a prolongation in movement time. When the reach trajectory is separated into the early and late phase of the reach (i.e., time from movement onset to peak velocity and peak deceleration to object contact, respectively), binocular advantage is more significant for the latter part of the movement. Specifically, when viewing with one eye, subjects spent a significantly longer amount of time in the deceleration phase (i.e., peak velocity to end of reach) (Servos, Goodale, Jakobson, 1992; Goodale, 2011; Jackson et al., 1997; Servos and Goodale, 1994; Keefe and Watt, 2017; Watt and Bradshaw, 2002; Bradshaw and Elliot, 2003), terminal reach phase (i.e., peak deceleration to end of reach) (Melmoth and Grant, 2006; Servos and Goodale, 1994; Bradshaw and Elliot, 2003; Bradshaw, Elliot, and Luffman, 2002), and grasping phase (i.e., end of reach to lifting the object) (Melmoth and Grant, 2006; Watt and Bradshaw, 2000; Gnanaseelan, Gonzalez, and Niechwiej-Szwedo, 2014; Servos and Goodale, 1994). Most studies that examined prehension reported increased grasp aperture (Keefe and Watt, 2009; Melmoth and Grant, 2006; Watt and Bradshaw, 2002; Bradshaw and Elliot, 2003), and a change in grip force scaling (Jackson, Newport, and Shaw, 2002) during monocular viewing. Additionally, studies that examined pointing only, showed increased end-point reach errors (Loftus et al., 2004; Heath et al., 2008). In contrast, binocular advantage has not been consistently reported for the early transport phase of the reaching

movement, representative of movement planning. Some studies reported reduced peak velocity and acceleration (Servos, Goodale, and Jakobson, 1992; Goodale, 2011; Gnanaseelan, Gonzalez, Niechwiej-Szwedo, 2014; Jackson et al., 1997) while others showed no significant effects (Bradshaw and Elliot, 2003; Watt and Bradshaw, 2002) under monocular viewing. Taken together, research suggests that binocular visual information plays an important role in the execution of skilled prehensile movements with stronger evidence supporting its importance during the deceleration phase of the reach and grasp execution.

Looking deeper into the movement parameters, it seems that binocular visual information is important for controlling the hand approaching the target and scaling the grasp aperture to match the object's shape, size, and orientation. Melmoth and Grant (2006) found that subjects adopted a more cautious approach under monocular viewing as they approached the object. That is, they pre-shaped their hand farther away from the target with a wider grip aperture, suggesting there was a larger uncertainty associated with using monocular input to plan the grasping movement. Similar results were seen from Jackson and colleagues (Jackson, Newport, and Shaw, 2002), who interpreted this finding to be due to altered visuomotor safety margins associated with uncertainty in the movement plan. Additional findings from Servos et al. (Servos, Goodale, and Jakobson, 1992) demonstrate that monocular viewing is associated with more online adjustments in grasp aperture during the reach phase, and grip formation during the closing phase of the grasp. Overall, these findings suggest that binocular viewing is associated with a more efficient grasping motor plan. Under monocular viewing subjects adopt a cautious strategy characterized by a prolonged deceleration phase in the terminal reach/grasp closing phase of the movement (e.g., Jackson et al., 1997; Goodale, 2011), more variability and errors, and less

stability in the reach (e.g., Heath et al., 2008) and grasp (e.g., Melmoth and Grant, 2006; Keefe and Watt, 2009).

Additional insight into the role of binocular input in movement planning and online control comes from Bradshaw and colleagues (Bradshaw and Elliot, 2003; Bradshaw, Elliot, and Luffman, 2002). In their study, subjects were presented with an initial monocular view of the object, and then binocular viewing was provided following movement onset during the entire movement execution (i.e., 100% binocular feedback) or for a percentage of movement duration (i.e., 25%, 50%, or 75% of movement duration). Results showed that kinematic indices of the early transport phase (i.e., peak wrist velocity and time to peak velocity) were not significantly different across the visual feedback conditions. In contrast, when binocular visual input was available for at least 50% of the movement duration, peak grip aperture, time in deceleration phase, and object contact duration were all reduced, which indicated better performance. In this study, all movements were planned based on monocular input, but results suggest that the CNS can update the initial plan using binocular information acquired early during the movement, and this is associated with improved grasp scaling and more efficient grasp execution.

Binocular advantage found in previous studies could arise due to stereopsis, disparity vergence, binocular summation, or a combination of these variables. However, the majority of previous studies manipulated vision in a binary manner – i.e., viewing was either with both eyes or with one eye – therefore, the contribution of these individual variables could not be examined. Only a few studies to date investigated which specific components of binocular vision are responsible for the behavioural advantage (e.g., Bradshaw et al., 2004; Melmoth et al., 2007; 2009). For example, Bradshaw and colleagues (2004) investigated prehension under 3 viewing conditions: 1) with stereopsis (i.e., two different views presented to each eye), 2) bi-ocular (i.e.,

two identical views presented to each eye; no stereopsis), and 3) monocular (i.e., one eye only). The findings showed that peak velocity was higher and peak grip apertures were smaller during binocular viewing with stereopsis in comparison to bi-ocular and monocular viewing conditions. The latter two experimental conditions were also associated with greater number of collisions and/or under-reaches. These results indicate that stereopsis provides important input for prehension.

Other studies that examined the contribution of stereopsis and disparity vergence, using base-out and base-in prisms (Mon Williams & Dijkerman, 1999; Melmoth 2007), showed that vergence angle may be particularly important during the control of the early reach component while stereopsis was seen to predominantly influence the late phase of the movement. For example, Mon Williams and Dijkerman (1999) reported that the magnitude of peak velocity and acceleration were lower, and the deceleration phase was longer when subjects wore base-out prisms, which induced a greater convergence angle. These findings were replicated and extended by Melmoth and colleagues (2007). These authors used prisms to disrupt the ocular vergence signal, and convex lenses to disrupt stereopsis. Results showed that when vergence was disrupted via prisms, pre-mature collisions and under-reaches were more frequent, which was dependent on the direction of the base of the lens (i.e., base-in or base-out). In contrast, terminal reaches and grip closure times were significantly slower and accompanied by multiple velocity corrections just before and after object contact when visual input (i.e., binocular disparity) was disrupted using plus lenses. These findings were consistent with another study that compared prehension performance in long-term stereo-deficient patients with healthy subjects with temporarily reduced stereoacuity (Melmoth et al., 2009). In that study, visual input was perturbed in visually normal subjects, using low- or high-plus lenses over one eye, to reduce

subjects' disparity sensitivity to a region of 200-800 arcsec and ~3000 arcsec, respectively. Compared to visually normal subjects, both stereo-deficient patients and subjects with artificially reduced stereoacuity had longer movement durations by ~100 ms. This was predominantly due to reaching deficits that occurred during the end-phase (i.e., prolonged final approach and more velocity corrections) and a doubling in error rates while executing the grasp (i.e., poorer coordination with object contact). Long-term stereo-deficient patients presented with particular deficits in controlling the post-contact phase (i.e., before objects were lifted) by prolonging the time spent applying the grasp by ~25% while subjects with course stereo-reductions presented deficits predominantly in the immediate pre-contact period (i.e., prolonged low velocity terminal reach and grip application: by 35 ms in low-plus and 65 ms in high-plus lens viewing). Taken together, these findings suggest that different components of binocular vision may be contributing to the control of distinct aspects of the prehensile movement. Particularly, the convergence angle is important in controlling the early phase of the reach while stereopsis is important in controlling the late, slow-velocity phase, as the hand approaches and grasps the target.

To summarize, research clearly demonstrates that binocular vision, particularly stereopsis, is important for controlling the terminal reach and grasp components. These studies demonstrated increased duration of the grasping phase (i.e., the time from when the hand makes contact with the object to the time the object is lifted) under monocular viewing. Taken together with the previously mentioned findings, these results may suggest stereopsis is critical for the efficient planning and control of the grasp phase, in addition to the terminal reach phase of the prehensile movement. In particular, stereopsis may be important for generating accurate and

precise forces to lift the object. However, the role of stereopsis in the control of grasp forces has not been previously investigated during prehension.

2.3 Grip Force as a Model for Predictive Control

Skillful performance of actions relies on motor planning (i.e., feedforward control) and online feedback to ensure that the movement execution is accurate and precise. The feedforward controller generates the initial motor command based on the initial state and the behavioral goal. This component is referred to as an open-loop system because it is not influenced by sensory feedback. As the movement is initiated, sensory receptors are activated and provide feedback (i.e., reafference) to the CNS, and this information is used to make corrections when errors are detected. Knowing the desired state from which the motor command was generated, the CNS can compare this with the actual state via the feedback controller. This will generate an error signal that is proportional to the difference between desired and actual feedback. This information is then fed back into the feedforward controller to be used for planning subsequent movements (Kandel et al., 2013; Miall and Wolpert, 1996). Feedback processes face an inherent limitation due to sensorimotor signalling delays, which depends on the modality. For example, stimulation of tactile receptors elicits activity in the primary somatosensory cortex at ~20 ms (Gobbelé et al., 2000), whereas visual stimuli are processed slower, with the first peak of activity in the primary visual cortex at ~60-90 ms (Di Russo et al., 2002). Due to the long delays associated with processing of visual sensory inputs, studies support the idea that the CNS controls movements via predictive control.

The study of motor control has provided several computational models which have been used to understand and explain how the brain is capable of compensating for the inherent

limitation of sensorimotor signalling delays. One that has been well reported in recent literature is the notion of the internal model. Fundamentally, motor commands arise through sensorimotor transformations. That is, these motor outputs are derived from sensory inputs (i.e., extrinsic information about the external environment and intrinsic information about our body) and converted into muscle contractions that generate movement. The CNS contains internal representations (i.e., “neural maps”) of sensory receptor arrays and the musculature. It also maintains internal representations that relate motor commands to the sensory signals expected as a result of the movement. Therefore, the internal model represents the causal relationship between actions and their consequences and, thus, enables the CNS to form a simulation of the intended movement without actually committing to the action (Kandel et al., 2013; Jordon, 1996; Kawato, 1999; Wolpert and Ghahramani, 2000; Flanagan et al., 2006). This consequently allows the CNS to select the most appropriate response or command for the intended action (Wolpert and Kawato, 1998; Haruno et al., 1999).

Earlier findings consisting of various object manipulation-based tasks demonstrate an ability for the CNS to perform anticipatory adjustments while performing complex movements with the upper limbs. This ability has been termed predictive control and is a well-documented component, both computationally and behaviourally, of the internal model. When holding an object with a precision grip, a minimal grip force (i.e., perpendicular to the contact surfaces) must be applied to prevent the object from slipping under the influence of external load forces (i.e., vertical lift forces, parallel to the contact surfaces). As well, excess force cannot be applied as it could damage the object and/or result in muscular fatigue. Results have shown that when subjects performed self-produced, cyclical hand-and-arm movements, grip force adjustments occurred simultaneously (or slightly before) the movement induced fluctuations in object load

force (Flanagan and Wing, 1995). These results suggest that the CNS anticipated the external, inertial forces induced from the object's acceleration. Similarly, when subjects pushed and pulled a manipulandum attached to a servo motor that induced a viscous load on the object, grip force and load force were coupled precisely in time (i.e., increased in parallel) (Flanagan et al., 2003). This showed that grip force was modulated in anticipation of the load force increase, which was later demonstrated to be present in all types of loads (i.e., viscous, inertial, and elastic loads) (Flanagan and Wing, 1997).

Many similar tasks have been used to support the idea that predictive (or anticipatory) control is an important feature of voluntary movements. It has been shown that both grip and lift forces are programmed to correspond with the visual cues of object properties (Gordon et al., 1993; 1991), such as object mechanical and material properties (i.e., densities and surface friction), weight, and shape (i.e., form and size). That is, based on the visual perception of object properties, a prediction was made as to what magnitude of grip force was required to successfully lift the object. For example, an experiment by Johansson and Westling. (1988a) involved subjects holding onto an instrument, with their right hand, while various objects were dropped into it. When subjects performed self-drops (i.e., with their left hand), grip force was applied predictively (i.e., parallel to load force increases). Most notably, this was consistent when varying object size and weight in combination with varying the surface friction of the instrument. Therefore, subjects learned to anticipate the changes in load forces and predict the required grip force magnitude based on several physical properties of both the dropped objects and the apparatus being grasped.

In contrast, reactive control is observed when there is a prediction error. For example, when the motor command cannot be generated predictively, and the CNS must engage in

feedback control. That is, grip force is modulated reactively in response to sensory feedback from tactile (i.e., from the finger tips), proprioceptive (i.e., from muscle spindles in the hand, arm, and shoulder), and visual feedback (i.e., following the completion of each sub-phase of the movement – e.g., following object contact, preceding object lift) (Johansson and Westling, 1987; 1984). Reactive control has commonly been characterized by a time lag in grip force application (Davidson and Wolpert, 2005), following an increase in load force, and an excess in grip force magnitude to compensate for the time lag (Johansson and Westling, 1988b). This was demonstrated in the previously mentioned experiment by Johansson and Westling. (1988a). When the object-drops were performed by the experimenter, rather than by the subject's left hand, the subject had no information regarding the physical properties of the object being dropped (i.e., its size constituting its weight and inertial resistance). When performing self-drops, the subject could acquire this information via tactile and proprioceptive feedback while holding the object with their left hand. Results demonstrated a significant lag in grip force application and increased safety margin. Additionally, grip force was too late to prevent slips.

From a computational viewpoint, predictive control offers two critical advantages. Most importantly, it compensates for sensorimotor signalling delays (Flanagan et al., 2006; Wolpert and Ghahramani, 2000; Miall and Wolpert, 1996). With feedback control, the CNS must wait for somatosensory feedback to be sent to the cortex before it can be processed, interpreted, and used to generate the error signal. This is known to take a considerable amount of time. However, with predictive control, the predicted sensory feedback is available immediately following movement initiation. Therefore, comparisons can be made online (i.e., during the execution of the movement) at any point during the movement. This enables the nervous system to make quick and accurate corrections as the error signal is representative of the present state of the body and

external environment. Secondly, with the ability for the inverse model to combine the learned dynamics of the object, arm, and hand (e.g., inertial properties) this reduces the level of inherent uncertainty of the motor command (Nowak et al., 2013; Wolpert and Kawato, 1998). That is, with feedforward control every motor command is inherently associated with uncertainty as the feedforward controller that generates the motor command based on desired state is not 100 percent accurate. The ability for the inverse internal model to anticipate sensory consequences as a result of the movement that the motor command generates enables the CNS to be more certain of the current command's endpoint accuracy. This is reflected in the size of the safety margin employed in the grasp (Nowak et al., 2013).

3.0 Current Study

3.1 Rationale

To summarize, it is evident that there is a binocular advantage from stereopsis on the terminal reach component of the prehensile movement. However, an interesting finding showing increased grasp duration during monocular vision poses the question of whether stereo-vision also influences the planning and control of the grasp phase. It is possible that stereopsis provides detailed, reliable depth information, regarding the physical properties of objects, which is critical for generating accurate and precise forces to successfully lift the object. Specifically, the detailed depth information enables the visuomotor system to engage in predictive control of the grasp, rather than reactive control, and perhaps this is what is reflected behaviourally during the grasping duration.

Figure 1 outlines the proposed mechanism that is believed to be occurring during the prehensile task. Beginning with the behavioural goal, that is picking up the object, the feedforward controller generates a motor command which is transmitted to the effectors (i.e., muscles of the arm and hand). Simultaneously, a copy of this information is sent to the internal model, which is believed to be located in the cerebellum, via an efference copy (i.e., corollary discharge) (Wolpert and Ghahramani, 2000; Kawato, 1999). The internal model simulates the movement based on the selected motor command and the internal representation of the object's properties and dynamics of the arm and hand. The simulation enables the internal model to generate a prediction of the sensory feedback of the movement as a result of the motor command. This information is sent back to the feedforward controller, in the form of a predicted error signal, in order to make adjustments to the motor command. This is done both prior-to and during (i.e., online) the execution of the movement, and therefore compensates for any

sensorimotor signalling delays that would be associated with a closed-loop, feedback control system. Once the motor command reaches the effector muscles the movement is produced, and the actual sensory feedback is compared with the predicted sensory feedback from the internal model. This generates an error signal (i.e., actual error) that can be used to update both the internal model and the feedforward controller for a subsequent movement.

Sensory input is believed to be critical to the processing of the internal model. Specifically, lack of reliable, detailed depth information from stereopsis may lead to greater uncertainty about object properties, which in turn leads to less efficient planning of grasp parameters. In other words, when stereopsis is absent or reduced, the visual input regarding object properties is less reliable which disables the internal model from generating an accurate prediction of the sensory consequences of the movement. Consequently, the CNS is forced to rely on feedback from tactile receptors in the fingertips and proprioceptive information from the limb to determine whether the object has been successfully grasped, and to adjust grip forces if required (i.e., closed-loop, feedback control) (see Figure 2). This additional processing inevitably leads to longer processing times and is believed to be the cause for increased grasp duration.

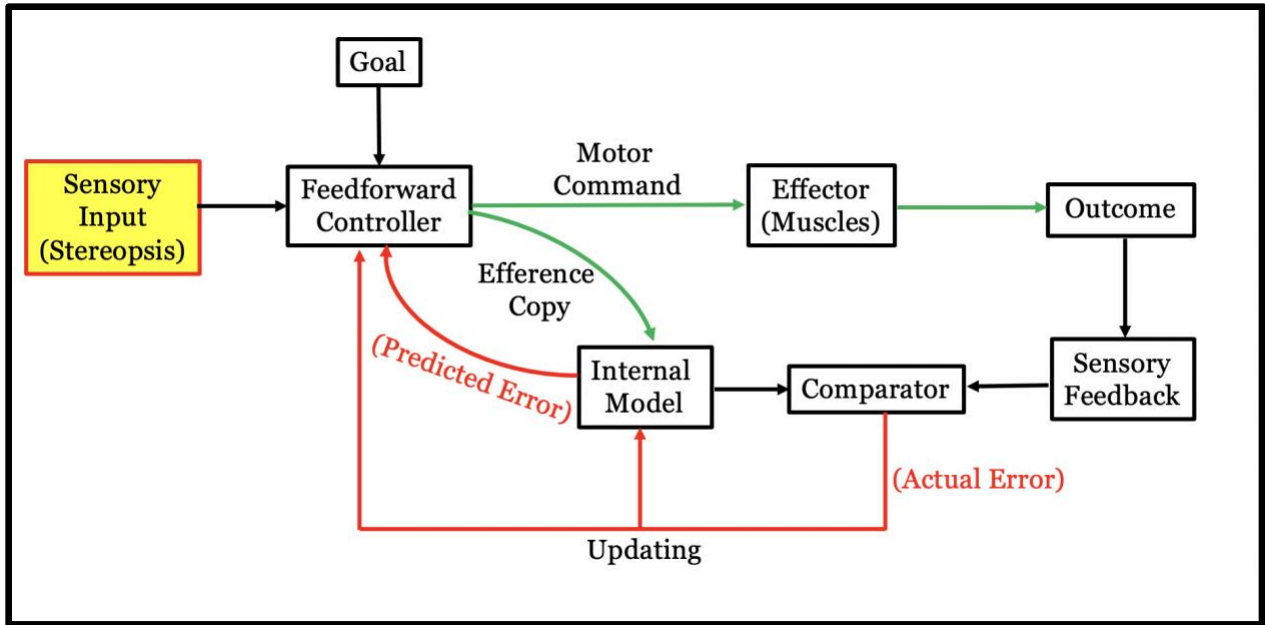


Figure 1. Hypothetical model to explain predictive control.

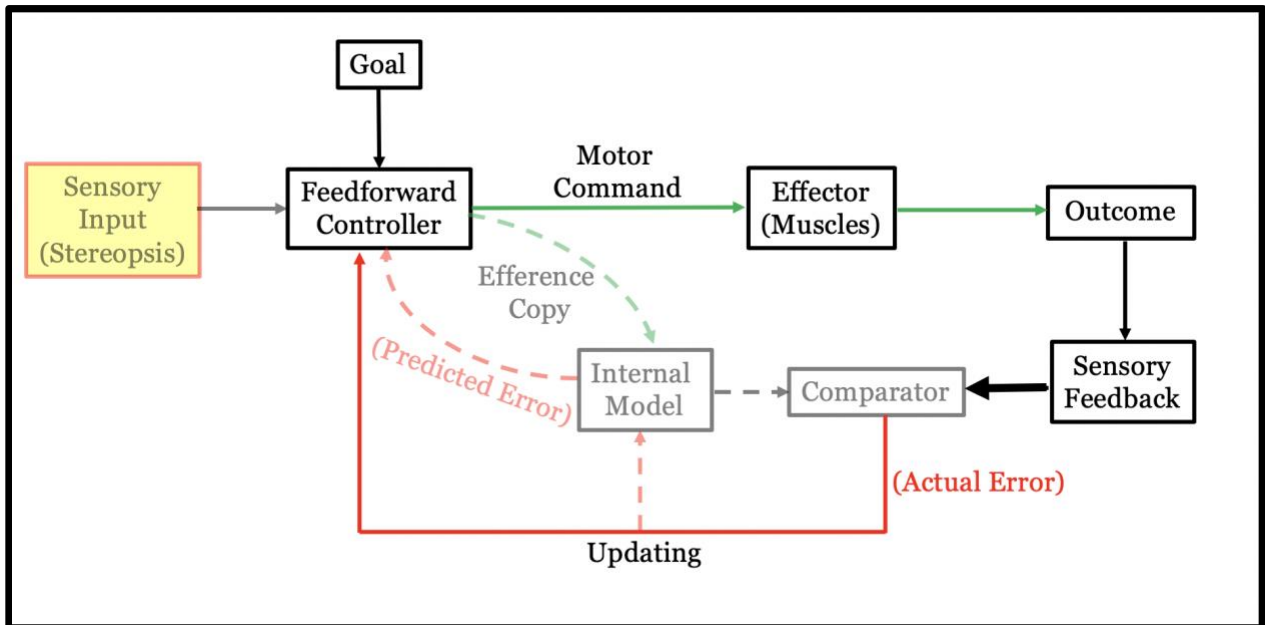


Figure 2. Feedback control as a result of a lack of visual sensory input to the predictive control mechanism.

3.2 Objective and Research Question

The aim of the proposed study was to investigate the role of stereopsis in the execution of grasping. The specific research question was: “What is the role of stereopsis in predictive control of grasping?”

3.3 Hypothesis

It was hypothesized that reduced stereoacuity will result in two main behavioural outcomes. First, grip force application will be less accurate and more variable. Secondly, there will be an increased reliance on feedback (i.e., reactive) control which will be reflected by a longer post-contact duration. Additionally, other than Melmoth et al. (2009), no study has manipulated stereoacuity to various degrees, but rather completely removed it. It was hypothesized that a gradual reduction in stereoacuity will be associated with a proportional reduction in behavioural performance, based on the aforementioned movement characteristics.

3.4 Methods

3.4.1 Subjects

Participants were recruited from the University of Waterloo student population. There were 11 males and 9 females between the age of 17 and 35 years. Recruitment consisted of advertisement posters placed on campus, rapid-fire class presentations, and email inquiries to students in University research laboratories. The study was approved by the University of Waterloo Ethics Board (ORE # 22999) and all participants signed a consent form. All participants were free from any history of neurological disorders or incidents (e.g.,

neurodevelopmental disorders, history of concussion or brain trauma). They were right-hand dominant and had normal or corrected-to-normal visual acuity (i.e., ≤ 0.1 log MAR) and stereoacuity (i.e., ≤ 50 arcsec).

3.4.2 Experimental Design

Initial Assessment

Visual acuity was assessed using the Bailey-Lovie vision chart, and the Randot® Stereotest was used to assess stereoacuity. Handedness was assessed using the Waterloo Handedness Questionnaire (Appendix A.1) and the Tapply and Bryden Tapping Task (Appendix A.2). Participants who failed the inclusion criteria were excluded from the study.

Experimental tasks

Prior to beginning the experimental protocol, subjects' stereoacuity was assessed while they were wearing a plus lens in front of their left eye. That is, the Randot® Stereo test was administered while the subject wore a plus diopter (i.e., convex) lens. The objective here was to determine which power of the lens was required to induce a visual perturbation such that the subject had a temporary stereoacuity between 100-200 arcsec (200 stereo condition) and between 400-800 arcsec (800 stereo condition).

Once the lens power to achieve the stereo manipulations was determined, the experimental task commenced. A description of the study design is illustrated in Figure 3. The experiment consisted of 4 visual conditions (i.e., monocular, 800 arcsec, 200 arcsec, and binocular), which served as blocks. Within each block, the target object was manipulated in size, texture/colour, distance – which included 10% of trials to serve as catch trials at a farther distance – and weight – which included 10% of trials with an additional weight attached in order

to serve as catch trials. These catch trials were not included in data analysis. A maximum of two identical trials were performed within each block. All trials were fully randomized within each block. Participants performed all experimental tasks in a single session.

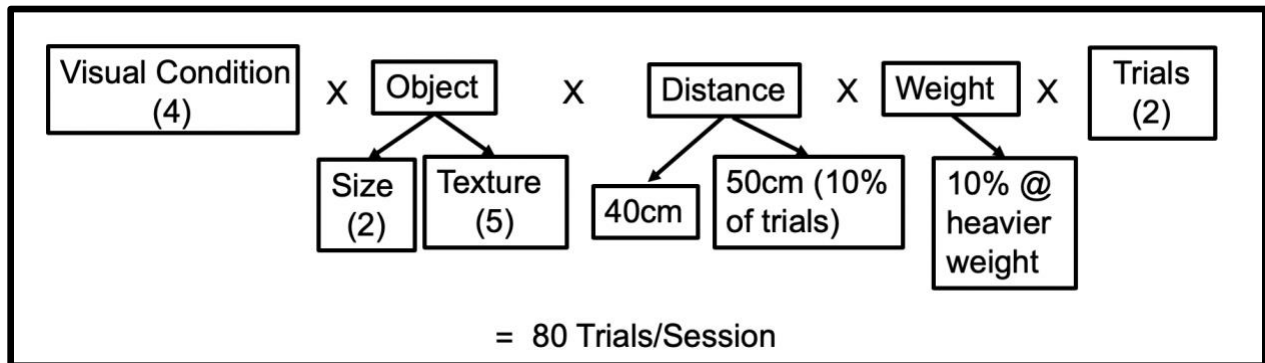


Figure 3. Diagram illustrating the experimental manipulations.

A total of 10 beads were used for the study, each with its unique physical properties. Beads varied in texture (i.e., 5 different textures), and size (i.e., small: 1.9 cm diameter; large 2.3 cm diameter). Five textures of beads differed in colour and roughness: white-smooth, white-rough, black-smooth, black-rough, gold-smooth. The purpose of introducing texture and size manipulations was to introduce variability to the object's properties and thus limit subjects' ability to form a sensorimotor memory regarding the object's properties. The aforementioned texture properties were selected based on a small perceptual experiment performed during piloting.

3.4.3 Apparatus

Figure 4 illustrates the experimental apparatus. Subjects were seated in a chair in front of a table and had their chin resting in a chin rest. Next to the chin rest, on the left side, was a metal

arm with a plus diopter lens attached to it. This arm was used to position the lens in front of the subject's left eye, much like a regular lens would on a pair of glasses. Lenses were selected based on initial assessment described above. The subject's right hand grasped a vertical needle, located 10 cm in front of their eyes, with the thumb and index finger. This needle functioned as the starting point for each reaching trial. It was below eye-level such that it was not in the line of sight. Two metal holders holding the beads were located in front of the starting needle, one directly in front of the other. The farthest one (i.e., marked by B; Figure 4) was placed in one of two locations: 40 cm or 50 cm in front of the eyes while the second holder (i.e., marked by C) was located 10 cm in front of the other holder.

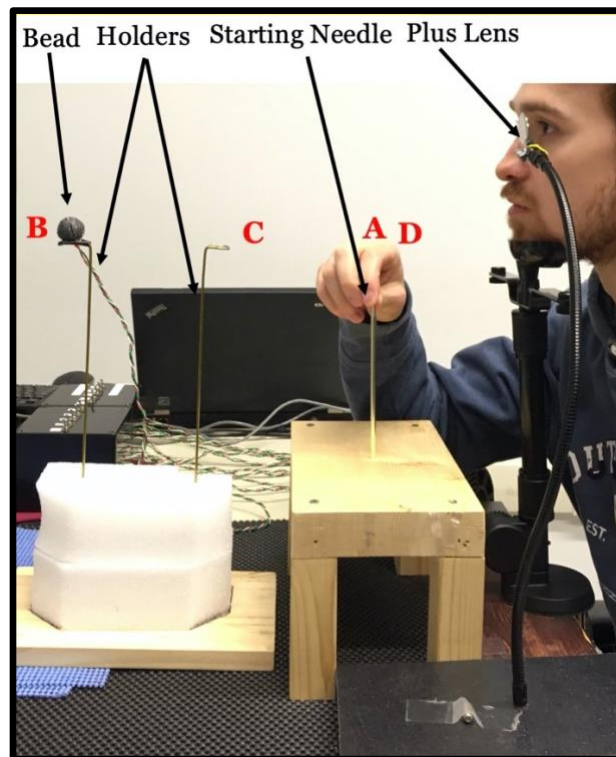


Figure 4. Experimental Apparatus.

Two types of datasets were recorded. Hand position data were recorded via the Optotrak motion capture system (Northern Digital Inc.) while two infrared reflective diodes were attached to the subject's index finger and thumb. The following coordinate frame was used: azimuth such that positive-x was to the right of the starting position, positive-y was in the downward direction, and positive-z was in front of the subject. These data were recorded with a sampling frequency of 250 Hz. Kinetic data were recorded via Honeywell® FSG Force Sensors (Figure 5, Appendix A.3). Each bead was instrumented with a force transducer embedded into the custom made, 3D-printed bead shell. These data were recorded from an analog signal with a sampling frequency of 1000 Hz. Kinetic and kinematic data were collected using the First Principles® software to ensure temporal synchronization.

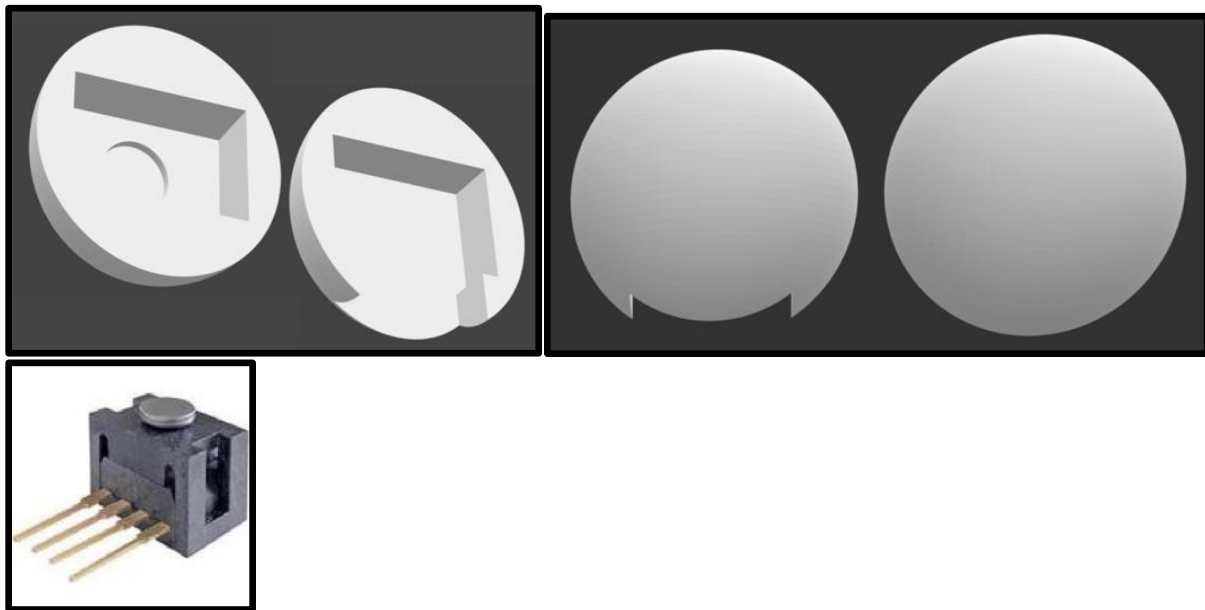


Figure 5. Illustration of bead apparatus instrumented with Honeywell® FSG sensors.

3.4.4 Procedures

Each trial began with subjects fixating on a dot at a distance of 80 cm with their hand in the starting location (see Figure 4 for illustration). An auditory cue was used as the “GO” signal, and as a trigger to begin data collection. Referring to Figure 4, subjects were instructed to reach and grasp the target bead from location B and transport it to location C, then return to the starting needle in location D. Subjects were instructed to perform this task as fast as possible, without dropping the bead.

Subjects were provided with 20 practice trials with a “practice bead” that differed from the experimental beads used for collection. The objective here was to familiarize subjects with the task. Following practice, one of the four lenses was installed onto the metal arm, thus inducing the visual manipulation and creating the respective visual condition. Subjects were provided 5 additional pre-block practice trials with the visual manipulation. The purpose of this was to allow the subjects to adjust to the refractive power of the lens and to eliminate any learning effect that may potentially contaminate the data. These practice trials were also performed with the same “practice bead”. Following practice, subjects performed the task described above. The experiment consisted of 4 blocks with the different visual conditions counterbalanced between subjects. Each visual condition consisted of a total of 20 recorded trials. Within each condition, the combination of bead parameters (i.e., texture, size, distance, weight) were randomized. Rest periods were provided between each block of collection. Figure 6 provides an overview of the experimental protocol.

20 Practice Trials	5 pre-Block Practice Trials	20 Trials	5 pre-Block Practice Trials	20 Trials	5 pre-Block Practice Trials	20 Trials	5 pre-Block Practice Trials	20 Trials
	Block 1 (e.g., 800 arcsec)		Block 2 (e.g., monocular)		Block 3 (e.g., 200 arcsec)		Block 4 (e.g., binocular)	

Figure 6. Overview of the experimental protocol.

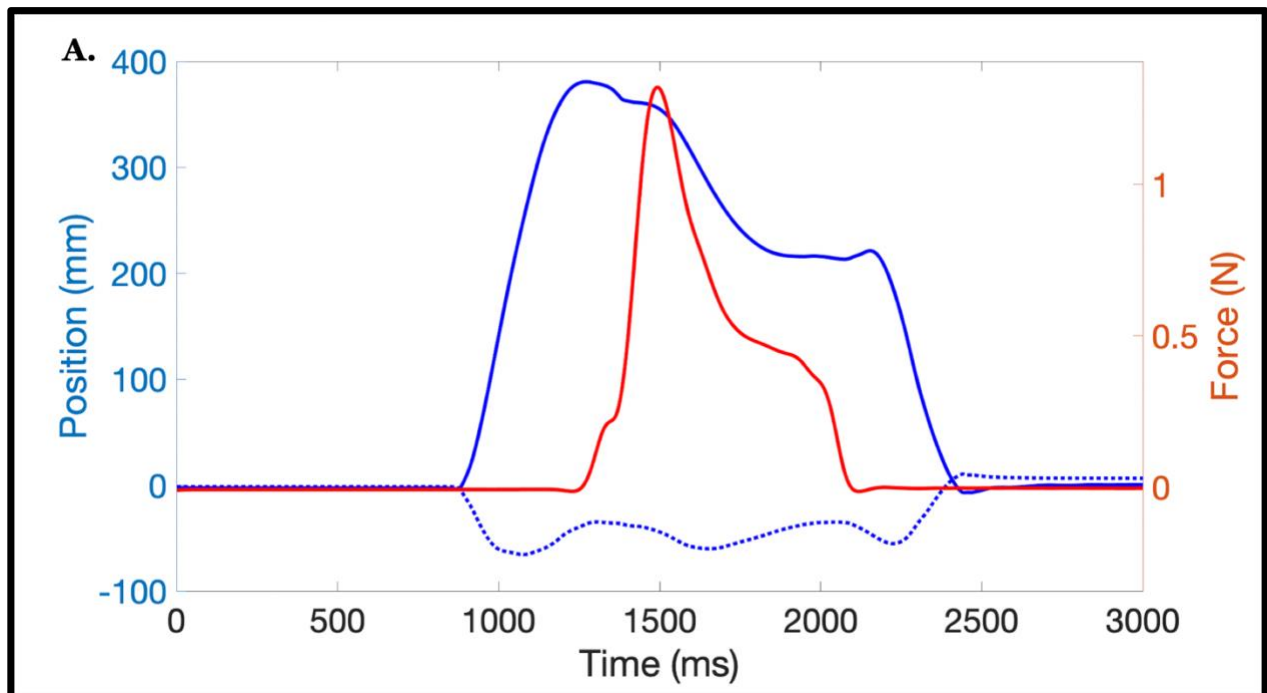
3.4.5 Data Analysis

Raw data were processed using a custom script developed using MATLAB R2018a software. The raw kinetic data were converted from volts to force by applying a calibration equation, specific to each sensor, which was obtained during pilot testing (Appendix A.4). Briefly, ten predetermined weights were placed onto the actuator of each force sensor and the voltage output was recorded. This process was done over three consecutive days to determine the repeatability of each force sensor. The ten weights were selected to cover a range twice the magnitude that would be applied to the sensors during the experiment. Following this, the voltage outputs of each sensor, for each day, were plotted and fitted with a linear calibration curve. The equations for each day were compared which confirmed the sensors to have a high degree of repeatability as there were no significant difference between the days. Thus, the calibration equation from the second day was chosen and applied to the raw dataset of each respective sensor. Kinematic data were interpolated (i.e., up-sampled) to 1000 Hz in order to temporally synchronize it to the kinetic dataset.

Both kinematic and kinetic data sets were processed using a 4th-order, low, dual-pass Butterworth filter with a cut-off frequency of 12Hz. Figure 7 displays a typical kinematic and kinetic profile during monocular viewing for a single trial. Kinematic hand position data and kinetic force data was plotted for each trial (e.g., Figure 7a). The derivative of both signals was calculated to determine the hand velocity and force rate of change profiles (e.g., Figure 7c). Each trial was screened to identify artefacts and outliers.

3.4.6 Outcome Measures

The aim of this study was to examine the role of stereopsis in grasp execution. Figure 7b depicts the temporal relationship between the hand velocity profile and the grip force magnitude profile and Figure 7c depicts the relationship between the hand velocity profile and the grip force rate of change profile. Several composite outcome measures among these profiles were extracted in order to examine different parameters of the movement to test our main hypothesis.



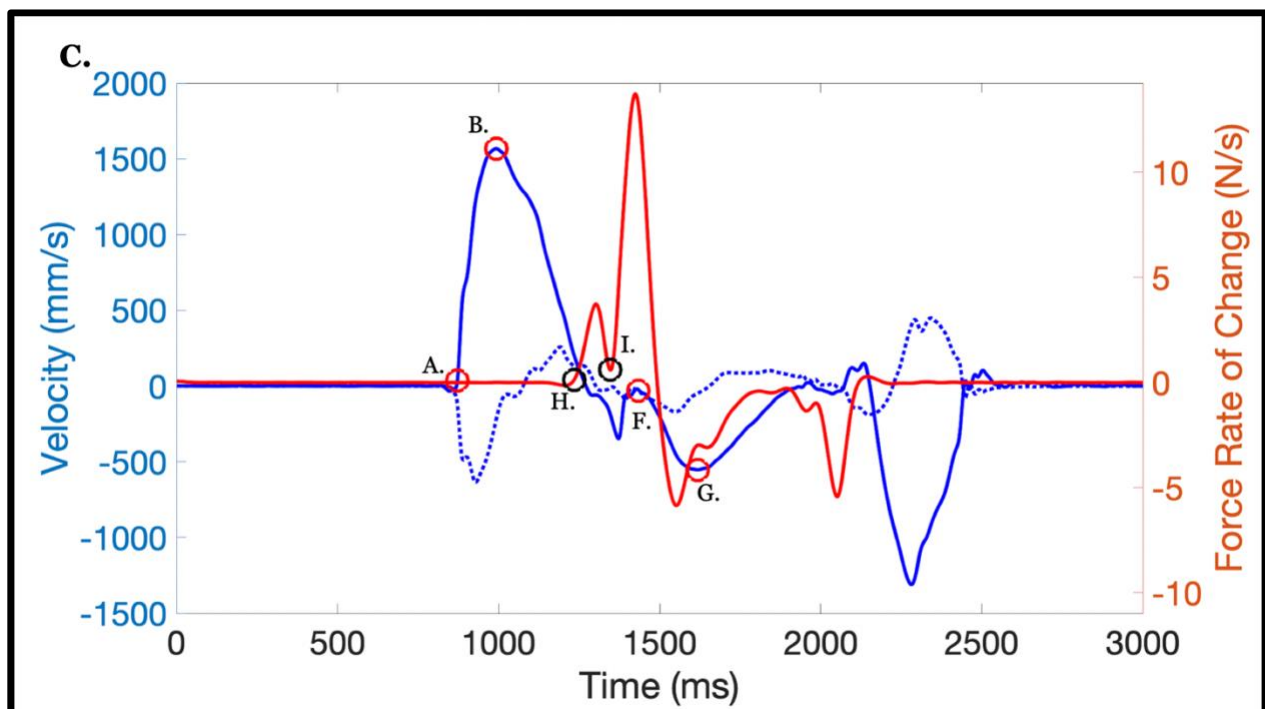
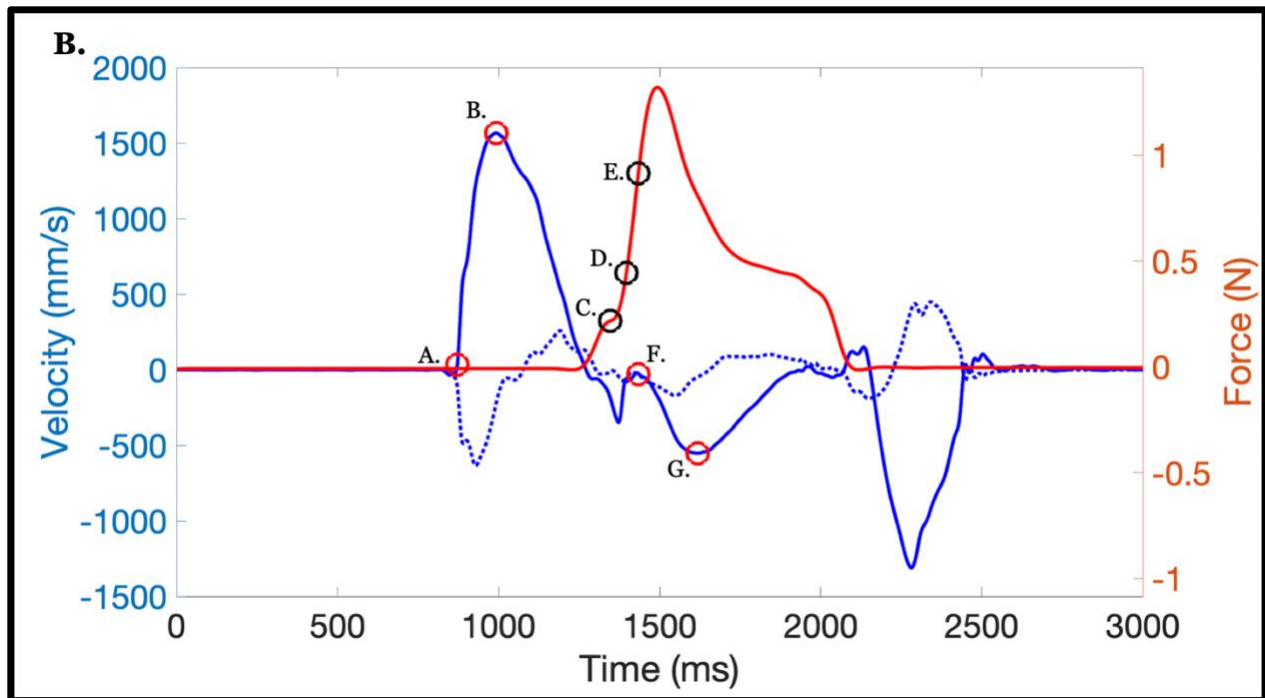


Figure 7. Typical trial illustrating a kinematic and kinetic profile during monocular viewing. A: Finger position in z-plane (solid blue), finger position in y-plane (dotted blue), and grip force profile (red). B: The derivative was calculated for the hand position signal, resulting in hand velocity in z-plane (solid blue) and hand velocity in y-plane (dotted blue) and grip force magnitude. Outcome measures include a: start of reach, b: reach peak velocity, c: time of grasp, d: grip force 50ms following grasp, e: grip force at time of lift-off, f: time of lift-off, g: transport peak velocity. C: The derivative was calculated for the force signal, resulting in grip force rate of

change (red). Hand velocity profiles remained the same from Figure 7b. Outcome measures include a: start of reach, b: reach peak velocity, h: time of object contact, i: secondary object contact, f: time of lift-off, g: transport peak velocity.

Movement Duration

Movement duration was defined as the time from the start of the reach (Figure 7c, marker “A”) to the time the digits made initial contact with the bead (Figure 7c, marker “H”). Movement onset was defined based on threshold criteria regarding the hand velocity profile in the forward, z-plane. Specifically, movement onset was defined as the time when hand velocity was greater than 30 mm/s. The time of object contact was defined based on threshold criterion of the force rate of change profile. Specifically, object contact was defined as when force rate exceeded 0.1 N/s.

Reach Peak Velocity

The peak velocity of the reach (Figure 7c, marker “B”) was defined as the maximum velocity of the index finger in the z-plane between the time of movement onset (Figure 7c, marker “A”) and the time of object contact (Figure 7c, marker “H”).

Acceleration Interval Duration (Reach Phase)

Acceleration interval duration was defined as the duration of the early component of the reach. Analytically, this was defined as the time from movement onset (Figure 7b, marker “A”) to the time of reach peak velocity (Figure 7b, marker “B”).

Deceleration Interval Duration (Reach Phase)

Deceleration interval duration was defined as the duration of the late component of the reach. Analytically, this was defined as the time from reach peak velocity (Figure 7c, marker “B”) to the time of object contact (Figure 7c, marker “H”).

Post-contact Time

Post-contact time was defined as the duration of time spent in the grasp phase. This was defined as the time from object contact (Figure 7c, marker “H”) to the time of object lift-off (Figure 7c, marker “F”). The time of object lift-off was the timepoint when the object was lifted from the holder in location “B” (Figure 4). Lift-off was defined when the hand velocity exceeded 30 mm/s in the vertical plane (Figure 7c, blue dashed line).

Grip Force 50ms following Grasp (GF@50)

GF@50 (Figure 7b, marker “D”) was defined as the magnitude of grip force 50 ms following the time of grasp (Figure 7b, marker “C”). “Grasp” was defined as the timepoint when a secure grasp was established. Video footage of the hand for each trial was qualitatively analyzed and it was determined that occasionally, subjects would first bump the bead with either the thumb or index finger. This collision was followed by a re-adjustment/re-application of grasp prior to lifting the bead. An example of this can be observed in Figure 7c where marker “H” was the initial contact (i.e., time of object contact) which was followed by a re-adjustment. Therefore, marker “I” was defined as the time of “secondary object contact” (i.e., force rate exceeded 0.1 N/s following re-adjustment). The time of “grasp” was then defined, based on a threshold criterion, as the time following “secondary object contact” when grip force magnitude exceeded

0.05 N. Once the time of “grasp” was extracted, the grip force magnitude 50 ms following “grasp” was extracted and defined as GF@50.

Variability in Grip Force 50ms following Grasp (GF@50)

Variability in GF@50 was defined as the within-subject variability in the GF@50 measure. Specifically, the standard deviation of the GF@50 measure was calculated for each subject, within each visual condition. This calculation was done in the Statistical Analysis stage, following the extraction of the outcome measures presented in this section.

Grip Force at Object Lift-off (GF@LO)

GF@LO (Figure 7b, marker “E”) was defined as the magnitude of grip force at the time of object lift-off (Figure 7b, marker “F”).

Grasping Errors

As mentioned previously, subjects occasionally bumped the beads with their digits prior to establishing a secure grasp. This collision was defined as “grasp error”. This was extracted by counting the number of trials where a grasp adjustment was present. Specifically, a function was created to detect whether a peak was present between the time of object contact (Figure 7c, marker “H”) and the time of object lift-off (Figure 7c, marker “F”), within the force rate of change profile. This is depicted in Figure 7c where a peak (i.e., local maximum) can be seen between marker “H” and marker “I” along the force rate profile (red line). During the Statistical Analysis stage, the number of trials with a “grasp error”, within each visual condition for each subject was calculated and further analyzed.

Acceleration Interval Duration (Transport Phase after Grasping the Bead)

Acceleration interval duration was defined as the duration of the early component of the transport phase (i.e., from location “B” to location “C”; Figure 4). Analytically, this was defined as the time from object lift-off (Figure 7c, marker “F”) to the time of peak velocity of the transport phase (Figure 7c, marker “G”).

Transport Phase Peak Velocity

The peak velocity of the transport phase (Figure 7c, marker “G”) was defined as the maximum velocity in the z-plane after object lift-off (Figure 7c, marker “F”).

3.4.7 Statistical Analysis

The extracted measures were analysed using R language (version 3.6.1) in RStudio. All measures were assessed for normality and screened for outliers (i.e., datapoints outside ± 3 standard deviations). The hypothesis was tested using a linear mixed model ANOVA (one-way, repeated measures design) and a Tukey’s Honestly Significant Difference (HSD) post hoc test.

3.5 Results

Table 1 reports the results (i.e., mean and standard error) from the three phases of interest from the prehensile movement. This includes the reach phase, grasp phase, and transport phase.

Table 1. Effects of viewing condition on prehension kinematics and kinetics (mean±SEM).

	Monocular	800 arcsec	200 arcsec	Binocular	F value
Reach 1 towards the bead					
Movement duration (ms)	471(17)	462(16)	454(14)	434(14)	F(3,57)=6.67, p<0.0001
Peak velocity (mm/s)	1498(62)	1501(57)	1505(55)	1541(60)	F(3,57)=1.24, p=0.3054
Acceleration Interval Duration (ms)	205(11)	202(10)	198(9)	193(10)	F(3,57)=2.97, p=0.0394
Deceleration interval duration (ms)	261(14)	258(15)	254(12)	241(12)	F(3,57)=3.05, p=0.0356
Grasp Measures					
Post-contact duration (ms)	156(9)	118(7)	110(5)	100(5)	F(3,57)=30.24, p<0.0001
Grip force at 50ms (N)	0.38(0.019)	0.45(0.017)	0.44(0.021)	0.49(0.020)	F(3,57)=15.95, p<0.0001
Grip Force Precision at 50ms (N)	0.13(0.0067)	0.14(0.009)	0.12(0.0078)	0.13(0.0081)	F(3,57)=2.84, p=0.0458
Grip Force at Lift-off (N)	0.59(0.041)	0.60(0.044)	0.51(0.043)	0.56(0.041)	F(3,57)=1.65, p=0.1887
Grasp Errors (% of trials)	37.32(3.826)	16.64(3.294)	17.44(2.825)	7.20(1.729)	F(3,57)=29.19, p<0.0001
Reach 2 towards the needle					
Acceleration interval duration (ms)	187(5)	178(4.5)	180(5)	172(5)	F(3,57)=5.04, p=0.0036
Peak velocity (mm/s)	589(20)	604(19)	605(19)	612(18)	F(3,57)=1.19, p=0.3208

Note: Bolded text in 'F value' column indicates a significant main effect

3.5.1 Reach-To-Bead Kinematics

There was a significant main effect of viewing condition on movement duration (*see Table 1*). Post hoc testing revealed a significant difference between binocular viewing and the 800 arcsec viewing condition, and binocular viewing and monocular viewing, which is depicted in Figure 8a. This indicates that the reach phase of the prehensile movement was influenced when a larger perturbation to stereoacuity was applied.

There were no main effects of viewing condition on reach peak velocity. As depicted in Figure 8b and Table 1, no trend appeared to be present between the viewing conditions indicating that degrading stereoacuity or removing binocular input had no influence on the peak velocity of the reach towards the bead.

There was a significant main effect of viewing condition on the acceleration interval duration. Post hoc testing revealed there to be a difference only between binocular viewing and monocular viewing, as depicted in Figure 8c. This indicates there was an influence from binocular viewing on the early phase of the reach (i.e., ~6% performance decrease from binocular to monocular viewing).

There was a significant main effect of viewing condition on deceleration interval duration. Post hoc testing revealed a significant difference only between the binocular and monocular viewing conditions, as depicted in Figure 8d. This indicates an influence from binocular viewing on the late component of the reach phase of the prehensile movement (i.e., ~8% performance decrease from binocular to monocular viewing).

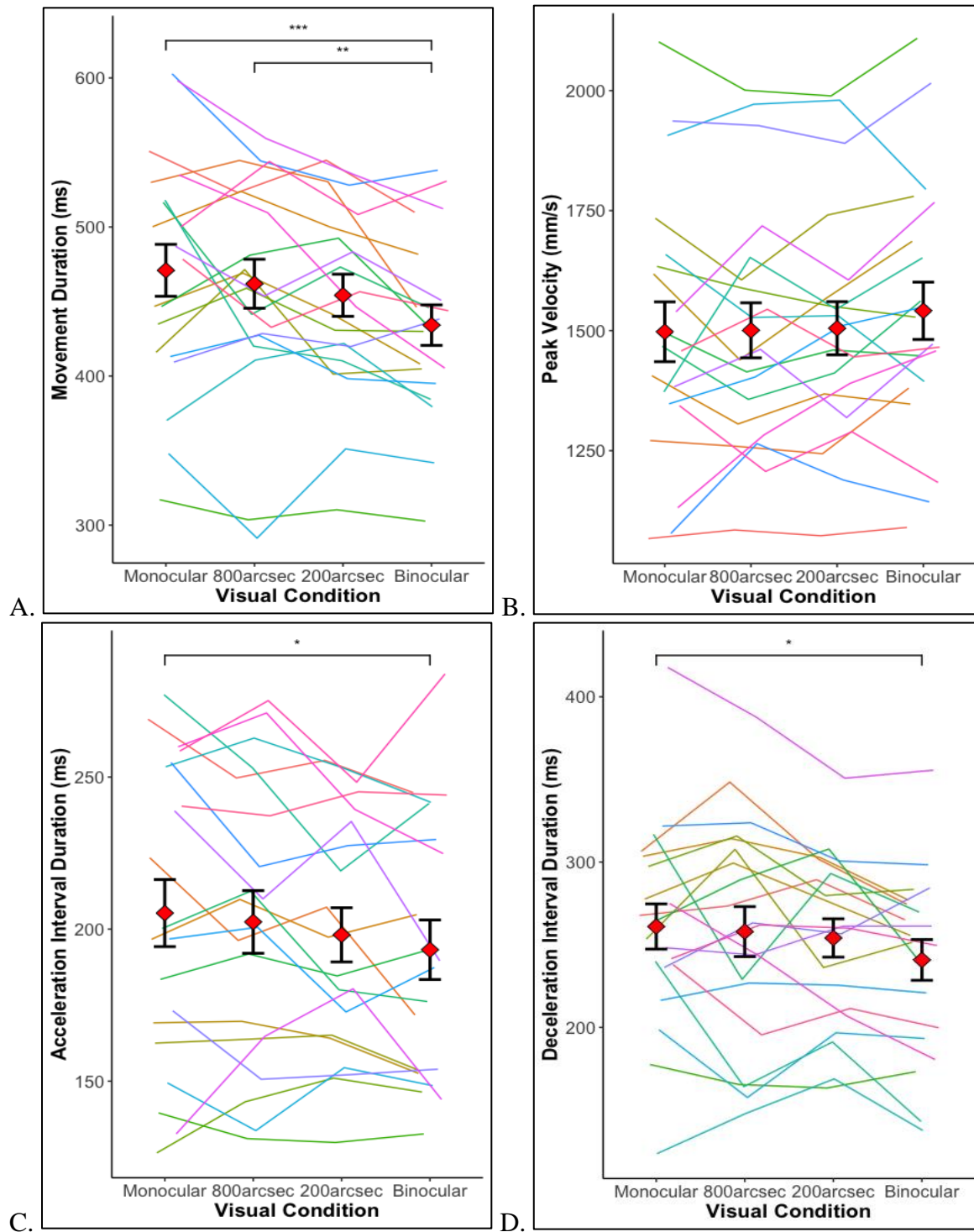


Figure 8. Kinematic results from the reach phase (i.e., reaching from location A to B). A: Movement Duration, B: Peak Velocity, C: Acceleration Interval, D: Deceleration Interval. Coloured lines represent individual subject means. Red diamonds represent between subject means. Error bars represent the standard error of the mean. Significance codes: ‘***’ = <0.001, ‘**’ = <0.01, ‘*’ = <0.05

3.5.2 Grasp Phase

Grasp duration

There was a significant main effect of viewing condition on post-contact time (Figure 9a). Post hoc testing revealed a significant difference between binocular viewing and both the 800 arcsec condition and the monocular viewing condition. Additionally, both the 200 arcsec condition and the 800 arcsec condition were significantly different from the monocular viewing condition in post-contact duration. These results support the hypothesis and demonstrate that stereopsis had a significant influence on post-contact time. Importantly, the effects on post-contact time were approximately 4.5-times larger compared to the effect of viewing condition on movement duration when reaching to the bead. Specifically, post-contact time increased by 36% from binocular viewing to monocular viewing in comparison to 8% for reach movement duration.

Grip force at 50ms following grasp

There was a significant main effect of viewing condition on grip force 50ms following grasp (GF@50). Post hoc testing revealed a significant effect between the binocular condition and all other conditions: 200 arcsec condition, 800 arcsec condition, and monocular (*see Table 1*). As displayed in Figure 9b, there were significant differences between the monocular condition and the 200 arcsec and 800 arcsec conditions. These results indicate that stereopsis had a significant influence on grip force programming, which is in direct support of our predictions. Additionally, the results reveal that, like the post-contact time, this effect is much larger than the effect on any measures during the reach phase – i.e., GF@50 demonstrated a 29% increase when comparing binocular to monocular viewing performance.

Grip force variability at 50ms following grasp

There was a significant main effect of viewing condition on the variability of GF@50. Post hoc testing revealed a significant difference only between the 200 arcsec condition and the 800 arcsec condition. Figure 9c depicts these results. This may indicate that perturbations to stereoacuity influenced the precision of GF@50.

Grip force at lift-off

There were no main effects of viewing condition on the grip force at the time of object lift-off. Figure 9d depicts the results and demonstrates that grip force at the time of object lift off was comparable across all viewing conditions.

Grasping errors

There was a significant main effect of viewing condition on grasp errors. Post hoc testing revealed a significant difference between all viewing conditions, except for the difference between the 200 arcsec and 800 arcsec conditions (*see Table 1, Figure 10*). This indicates that reducing stereopsis is associated with lower grasping efficacy, specifically the grasp application.

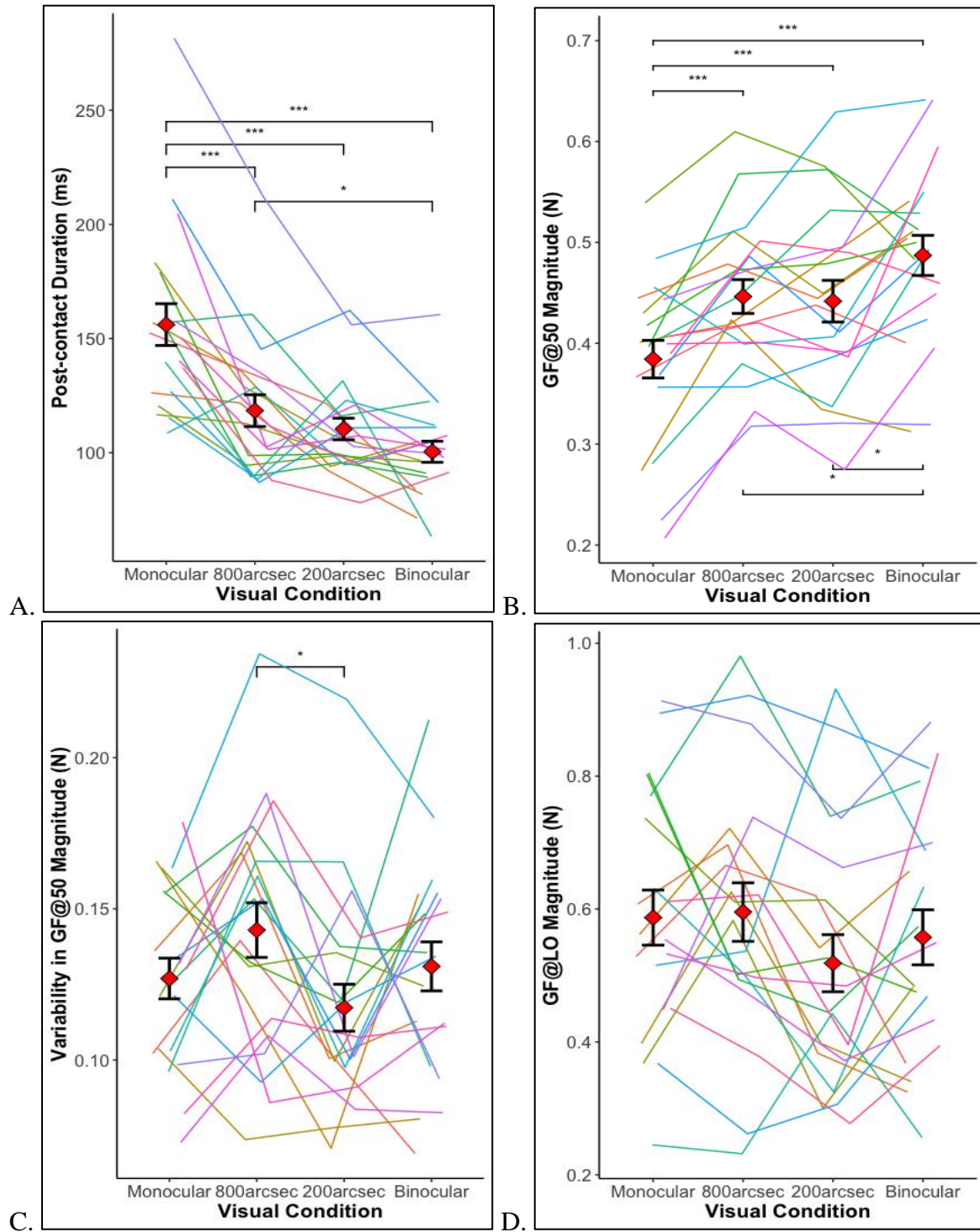


Figure 9. Results from grasping phase. A: Post-contact Duration, B: Grip Force Magnitude 50ms following Grasp, C: Precision in Grip Force 50ms following Grasp, D: Grip Force Magnitude at Object Lift-off. Coloured lines represent individual subject means. Red diamonds represent between subject means. Error bars represent the standard error of the mean. Significance codes: '***' = <0.001 , '**' = <0.01 , '*' = <0.05

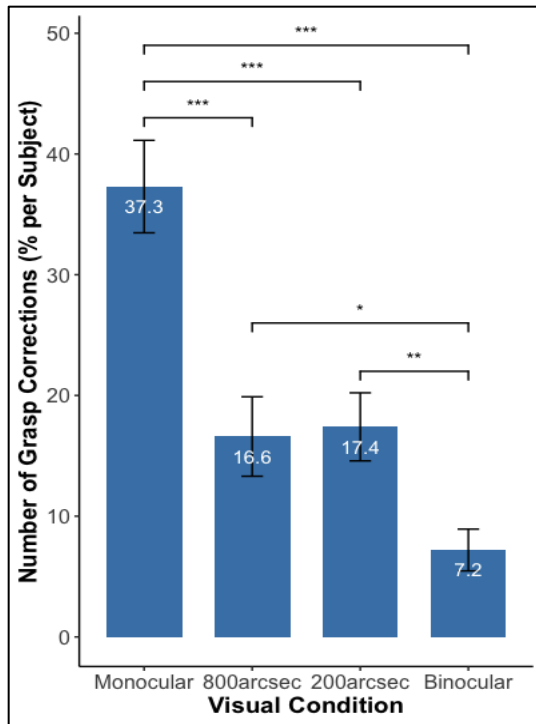


Figure 10. Errors in grasping. Column bars represent mean percent error, per subject. Error bars represent the standard error of the mean. Significance codes: ‘***’ = <0.001, ‘**’ = <0.01, ‘*’ = <0.05

3.5.3 Transport Phase to Needle

Acceleration interval duration

There was a significant main effect of viewing condition on the duration of the acceleration interval during the transport phase. Post hoc testing revealed a significant difference only between binocular and monocular viewing as described in Table 1 and displayed in Figure 11a. This indicates that removing binocular input had a significant effect on the duration of the early component of the transport phase after grasping the bead, however, residual stereoacuity was sufficient to maintain the same level of reach performance as binocular viewing.

Transport peak velocity

There were no significant effects of viewing condition on the peak velocity of the transport phase as shown in Figure 11b.

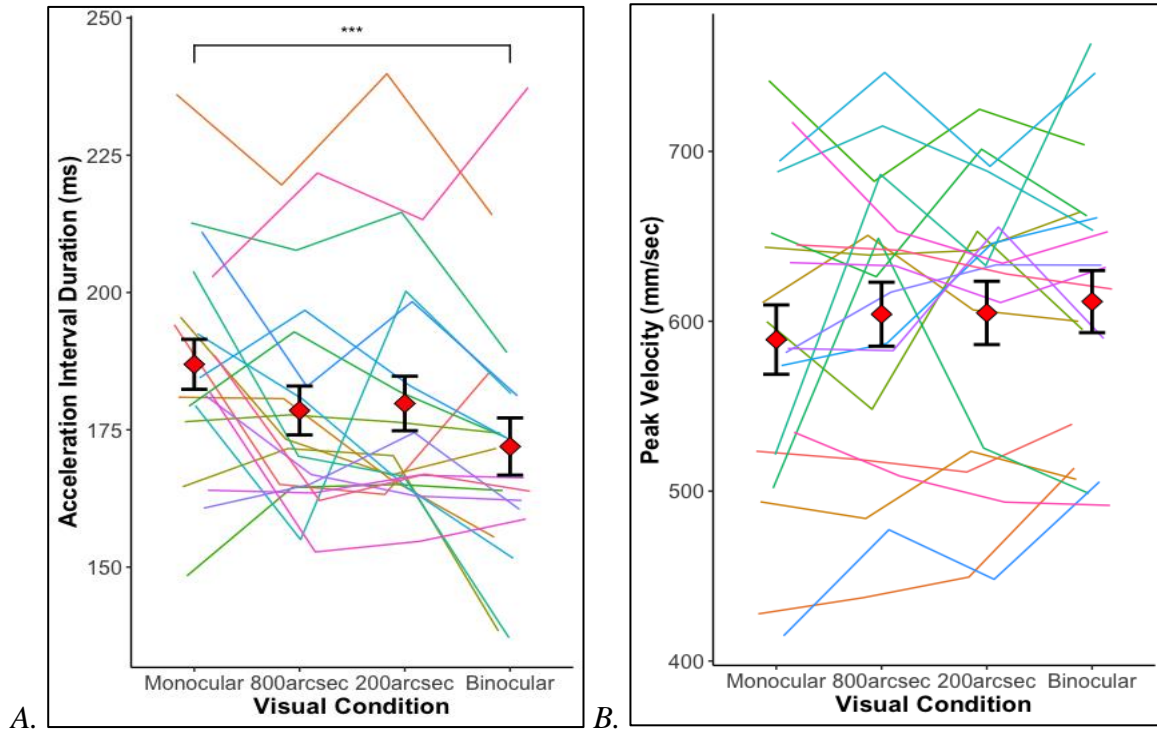


Figure 11. Results from transport phase. A: Acceleration Interval, B: Peak Velocity. Coloured lines represent individual subject means. Red diamonds represent between subject means. Error bars represent the standard error of the mean. Significance codes: ‘***’ = <math><0.001</math>, ‘**’ = <math><0.01</math>, ‘*’ = <math><0.05</math>

3.6 Discussion

The objective of the present study was to investigate the role of stereopsis in predictive control of grasping. Previous literature demonstrated a prolonged grasping interval, defined using kinematic measures during monocular compared to binocular viewing. The current study extends these findings by showing that a progressive reduction in stereoacuity is associated with a lower initial force application, which consequently leads to a longer post contact time. The

remainder of this section will discuss these behavioural findings in the context of previous literature, and discuss the mechanisms involved in central nervous system control of grasping.

Binocular viewing is associated with a significant advantage for grasp execution

Results from the current study indicate that binocular viewing had a predominant influence on the grasp phase of the prehensile movement, whereas the effect on the reach and bead transport phase was relatively smaller. The present results are consistent with previous literature demonstrating an influence from binocular vision on the late component of the reach phase and grasp application. Specifically, movement parameters such as reach duration and the duration of the deceleration interval typically demonstrate an approximate increase of 3-8% during monocular viewing when compared to binocular viewing (e.g., Servos and Goodale, 1994; Jackson et al., 1997; Watt and Bradshaw, 2002; Bradshaw and Elliot, 2003). In contrast, Servos, Goodale, and Jakobson (1992) demonstrated a 20-30% increase in these measures during monocular viewing. This discrepancy may be due to the nature of the task. That is, the latter study used an experimental paradigm where participants did not receive visual input in advance of a go signal (i.e., lights turned on the moment the auditory ‘go’ cue was presented). Therefore, this manipulation might have placed more constraints on movement planning and resulted in longer movement duration during monocular viewing.

The current results demonstrated a substantially larger influence on parameters involved in the grasp phase. When comparing performance between monocular and binocular viewing, measures including post-contact duration, GF@50, and grasping errors demonstrated an increase of 36%, 29%, and 30%, respectively. In contrast, an 8% increase was observed for the duration of the acceleration interval of the subsequent transport phase after the bead was lifted. No

previous studies have investigated the effect of monocular viewing on subsequent movement execution (i.e., the transport component after grasping), thus, this study provides new insight into the role of binocular viewing in performing movement sequences. Overall, the present results demonstrate consistency to previous literature regarding reduced performance in parameters relevant to the grasp phase. Specifically, a review of the literature revealed post-contact time to have an increase of approximately 16-23%, while other measures, which included grip aperture scaling and grasp errors experienced a ~2-14% and 33-64% increase, respectively (Bradshaw and Elliot, 2003; Servos and Goodale, 1994; Gnanaseelan, Gonzalez, Niechwiej-Szwedo, 2014; Watt and Bradshaw, 2000; Melmoth and Grant, 2006; Jackson, Newport, Jakobson, 2002; Keefe and Watt, 2009; Loftus et al., 2004; Heath et al., 2008; Watt and Bradshaw, 2002; Bradshaw and Elliot, 2003). Overall, the evidence provides a clear indication that the binocular advantage influences each phase of the prehensile movement independently. However, it is predominantly evident in the grasp phase of the prehensile movement.

Binocular stereopsis contributes to more efficient grasp force application

The current study provides novel and important knowledge about the role of binocular viewing in the control of force application during grasping. Specifically, our results showed that monocular viewing, as well as the two binocular viewing conditions with reduced stereoacuity, were associated with a significantly lower force during the early grasping phase (i.e., 50 ms after object grasp - GF@50). This may be indicative of a more cautious grasp application due to removal or reduction of binocular disparity cues. Specifically, stereopsis from binocular disparity provides the most accurate and reliable relative depth cue (Ono et al., 1977), which is important for extracting object properties, such as size, texture, or material. Accurate encoding of object

properties is critical for accurate programming of grasp forces. For example, grasp forces are higher for objects that are perceived as larger or more slippery (e.g., Gordon et al., 1991). Thus, it is possible that stereopsis provides an important input for accurate perception of object properties, which is critical for grasp execution.

Binocular vision contribution to prehension has been studied mainly by comparing performance while viewing with both eyes or one eye (e.g., Melmoth and Grant, 2006; Bradshaw and Elliot, 2003; Watt and Bradshaw, 2000). In contrast, only three previous studies investigated which components of binocular visual processing contribute towards the behavioural advantage. First, Bradshaw and colleagues (2004) demonstrated that improvement in prehensile performance is evident only when disparity information is available. Specifically, the authors used an elegant experimental paradigm to show that bi-ocular viewing – that is, where both eyes received visual input but disparity information was not available – was associated with similar prehensile performance as monocular viewing, and both these conditions were significantly worse in comparison to binocular viewing with disparity cues. In the other studies, Melmoth and colleagues (2007; 2009) used convex lenses to progressively reduce disparity to 800 arcsec and 3000 arcsec while participants performed a grasping task. Results showed that in comparison to binocular viewing these manipulations were associated with a progressive increase in grasp duration and grasping errors. Overall, these studies demonstrate the importance of disparity input in grasp execution; however, they do not reveal a mechanism that could account for the advantage.

The present study was designed to build on the previous literature by investigating the mechanism to explain the contribution of disparity to improved grasping performance. Our results demonstrate a relation between a reduced level of stereoacuity and two grasp-related

parameters: post-contact time and grasp force. While post-contact time has been reported in previous studies, the current study is the first to assess grasp forces while manipulating the level of stereoacuity. Extensive research shows that grasp forces are generated predictively based on the current visual input and prior experience (e.g., Gordon et al., 1993;1991); therefore, examining grasp forces provides insight into predictive control of grasping. Specifically, in this study, force was examined at 50 ms following object grasp (GF@50), which is a timepoint that is unlikely to be influenced by sensory feedback (Kandel et al., 2013) as it takes >50 ms for somatosensory feedback to influence the ongoing movement. In support of our hypothesis, the results showed that in comparison to normal binocular viewing, GF@50 was significantly lower with reduced stereoacuity, and further reduced in the monocular condition. Thus, experimental results support that stereopsis provides critical input for grasp execution, and in particular, for the predictive generation of grasp forces. Notably, even a relatively mild disruption to stereopsis (i.e., 200 arcsec) was associated with a slight, but significant reduction in GF@50. Conversely, a coarse level of stereopsis (i.e., 800 arcsec) conferred a significant advantage for programming grasp forces in comparison to the monocular viewing condition.

Perturbations to stereoacuity shift CNS control from predictive to reactive

Findings from this study suggest that a reduction in stereoacuity leads to a shift in CNS control from predictive to reactive control of grasping. Overall grasping performance was less efficient when stereopsis was reduced or absent as indicated by a higher percentage of grasp errors. Similarly, initial grasp force was lower and post-contact time was progressively longer with reduced stereo acuity. Taken together, reduced initial force application and prolonged grasping time are believed to be indicative of increased uncertainty and greater reliance on

reactive control, which in this case involves additional processing of somatosensory feedback from tactile receptors once the object is contacted by the digits in order to adjust the force level and successfully lift the object.

Behavioural literature has demonstrated that following perturbations to binocular vision there is a change in grasping kinetics and kinematics. Altered visuomotor safety margins can be manifested as a deficit in grip aperture (Watt and Bradshaw, 2002; Bradshaw and Elliot, 2003; Keefe and Watt, 2009; Servos, Goodale, Jakobson, 1992) or a deficit in grip force scaling (i.e., the ratio between grip force and vertical load force to prevent object slips) (Jackson, Newport, Shaw, 2002; Jackson, Newport, Shaw, 2002), which are both characteristic of a more cautious execution of the grasp. Specifically, it was observed that subjects extended the end phase of reach and pre-shaped their hand with a wider grip aperture further away from target whilst still poorly coordinating with the target by inaccurately scaling to the object's dimensions (Melmoth and Grant, 2006), and reducing their grip aperture in order to reduce possibility of a collision at object-contact (Gnanaseelan, Gonzalez, Niechwiej-Szwedo, 2014).

Computational studies in the field of robotics proposed slip prediction models whereby predictive internal models are programmed enabling robotic hands to detect and reduce the risk of object slippage by controlling the normal force (i.e., grip force). Consistent across this work is that all these models accurately and efficiently represent and process various input features of tactile data, via high-grade tactile sensors, to ensure grasp stability and slip prediction (Petchartee and Monkman, 2007,2008; Song et al., 2012; Agriomallos et al., 2018; Veiga, Peters, Hermans, 2018; Zapata-Impata, Gil, Torres, 2019). Behavioural studies investigating slips are consistent with this line of work. For example, the contribution of visual and tactile sensory information as the input to the internal model has been demonstrated (Jenmalm, Dahalstedt,

Johansson, 2000; Hadijosif and Smith, 2015). Specifically, these sensory inputs influence predictive control in order to maintain an appropriate safety margin and accurately scale grip force and grip aperture. In particular, when visual input regarding object properties was absent, subjects either failed to break gravitational force or overshoot the required grip force for grasps programmed for a light and heavier weight, respectively. In both cases of erroneous predictions, corrections were delayed until the initially programmed commands were terminated by somatosensory feedback (Johansson and Westling, 1988b). In other words, feedback from cutaneous afferents provided information regarding the frictional condition between the digits and object to allow for adaptation of force application via the detection of slips (Johansson and Westling, 1987;1984).

In the present study, a progressive decrease in GF@50 magnitude in response to a reduction in stereoacuity was observed. Taken together with both the behavioural and computational evidence in the literature, this finding could reflect increased uncertainty regarding grasp parameters of the motor command. In other words, the internal model lacked precise information regarding the physical properties of the target objects (i.e., surface friction, weight, curvature, size). Thus, a more cautious approach was programmed to allow more time for tactile sensory information to be processed in order to make necessary adjustments for digit placement and grip force application. Notably, there was no significant difference among viewing conditions in the grip force at lift-off. This suggests that by the time the object was lifted the CNS had acquired and processed the necessary information via non-visual sensory input for the movement to continue successfully (i.e., with an acceptable level of certainty). In all, these results suggest that binocular disparity provides important sensory input for the internal model to generate accurate predictions for grasp execution. In cases when disparity input is reduced, the prediction from the

internal model is less accurate/precise; thus, it is likely that the internal model has to rely on additional processing of sensory feedback from the somatosensory system in order to make the necessary adjustments to the grasp and confirm that grasp is accurate and sufficient to complete the task successfully.

Interestingly, this poses the question of whether this shift in control is simply a change in execution strategy, manifested as a more cautious approach, or whether there is an up-regulation in the neural areas responsible for processing tactile and proprioceptive feedback. Perhaps rather than a change in strategy where the motor control system relies more on somatosensory feedback, it up-regulates these neural areas in the primary somatosensory cortex in effort to re-weigh this information. It may be that the reduction or lack of disparity input leads less reliable input about object properties which might be associated with a less reliable predicted error signal sent to the feedforward controller. This information, in turn, could be used to trigger re-weighting of sensory information. In other words, reduced reliability of visual input could lead to up-regulation of the processing of somatosensory information from tactile and proprioceptive receptors in the upper limbs, via the feedback control mechanism. Unfortunately, this particular question cannot be answered by the present study as no neurophysiological measures were recorded. Thus, based on the present results it cannot be definitively established whether a reduction in stereoacuity results in a progressive shift from predictive to reactive control due to a change in a behavioural strategy or an upregulation of somatosensory feedback processing.

Neural correlates of predictive control during grasping

It is believed that the predictive control mechanism – whereby online corrections are made based on the internal representation of the movement dynamics (i.e., arm and hand kinematic and

dynamic models) and object physical properties – is part of the cortico-spinocerebellar-cortico pathway. That is, the internal representation is located within the spinocerebellum. The efference copy is compared to the internal representation, and the predicted error signal is relayed to the ventrolateral thalamus and then to its respective topographical location in the primary motor cortex (Kandel et al., 2013). Alternatively, there are axons exiting the interposed nucleus, entering the red nucleus and re-entering the spinal cord. Perhaps the adjustments to the motor command could be applied this way as well. In all, the current motor control literature suggests the intermediate parts of the spinocerebellum are where the predictive control mechanism, by which anticipatory adjustments are possible, is housed.

Reducing visual acuity in one eye impaired extraction of disparity information, which most likely reduced activity of the binocular neurons in the primary visual cortex. Binocular neurons are found in most areas of the posterior parietal cortex (PPC) (Sakata et al., 1997; Sakata, 1999) as well as in some areas of the temporal cortex (Uka et al., 2000; Watanabe et al., 2002), which include regions involved in the sensorimotor transformation for reaching and grasping movements. Specifically, these binocular neurons provide important information regarding object properties (e.g., relative size, orientation, texture). Additionally, there is evidence suggesting some degree of interaction between these visual pathways prior to that information entering motor cortical regions (Sakata et al., 1999). From the extrastriate cortex, information is transmitted via the posterior parietal cortex to the pre-motor and supplementary motor areas concerned with extrinsic information regarding the planning of the voluntary movement, and contextual control (i.e., selecting and executing the appropriate voluntary actions), respectively. Thus, perturbing stereoacuity would reduce the reliability of the sensory input and affect the sensorimotor transformation process. It is important to note that subjects were provided adequate

practice, under normal viewing conditions, which would have enabled an appropriate internal representation of movement dynamics (i.e., arm and hand kinematics and dynamics) to be formed. During full binocular viewing conditions, the motor command was generated and processed via the internal model to obtain the predicted error signal which could then be used to make anticipatory adjustments/corrections during early movement execution. Conversely, during perturbed visual conditions it appears that the predictive mechanism was less efficient because our results show more cautious grasp execution, possibly indicating greater reliance on feedback control, which is supported by increased post-contact duration and lower initial force application. In conclusion, the present results are believed to demonstrate a connection between stereopsis (i.e., binocular disparity information) and predictive control. A lack of disparity information resulted in a reduction to the functioning of the internal model thereby resulting in lower levels of predictive control while increasing levels of reactive control.

3.7 Conclusion

This thesis builds on the current understanding of visual contributions to prehensile movement via the recording of grasp forces. We demonstrate that the binocular advantage extends its influence past just the reach phase and predominantly influences the grasp phase. Specifically, parameters of the grasp phase demonstrated a significantly greater reduction in performance during monocular viewing relative to parameters of the reach and transport phase. Additionally, we demonstrate that stereopsis provides critical input for grasp execution, and in particular, for the predictive generation of grasp forces. The relationship between the level of stereoacuity present appears to be somewhat proportional to the level of predictive capabilities. That is, even a relatively mild disruption to stereopsis resulted in a slight but significant

reduction in force magnitude. Finally, these findings suggest binocular disparity provides important sensory input for the internal model to generate accurate predictions for grasp execution. In cases when disparity input is reduced, the prediction from the internal model is less accurate/precise; thus, the internal model has to rely on additional processing of sensory feedback from the somatosensory system in order to make the necessary adjustments to the grasp. Overall, this work identifies the role that stereopsis plays in grasp planning and execution which broadens the understanding of how binocular vision is involved in the control of fine motor skills involving the hands. Additionally, this work highlights some of the consequences of visual impairment on upper limb movement control and in turn has some functional implications to upper limb function.

3.8 Limitations

There are several notable limitations associated with this study which should be addressed in future investigations. Firstly, as mentioned previously in the discussion section, the present study did not record neurophysiological measures. This limits our ability to determine whether the shift in CNS control is simply a change in execution strategy or whether there is an up-regulation in the neural areas responsible for processing tactile and proprioceptive somatosensory feedback. This question could be investigated using electroencephalography (EEG) which provides a direct measure of excitability of neural networks. This would have an important influence on the interpretation of the current dataset. It would enable us to confirm that, following reductions to stereoacuity, there is selective re-weighting between the available sources of sensory input which would add another layer of understanding to this control mechanism.

The second limitation involves the interpretability of the H-I interval during the grip rate of change profile (Figure 7c). The present study had regarded the local maxima following marker “H” as a grasping error representing an initial collision between the target object and the index finger or thumb. However, it can be argued that there is important tactile information being conveyed from this event. We cannot completely disregard the possibility that perhaps subjects are adopting this collision as part of their reach strategy to acquire information for the grasp. In other words, subjects may simply decide to commit a collision to acquire more information regarding the bead’s physical properties to aid in the grasping phase. If this were so, this would suggest that processing of somatosensory information begins much earlier than from the time of grasp and could strongly influence the outcome of the result. However, a counter argument to this is that there is no useful information regarding the beads (i.e., size, weight, texture) being conveyed from this collision. At best, the information acquired from the contact of the collision would provide a confirmation of bead location – i.e., confirm to the subject that they have reached the bead. This we believe to be true since when the bead comes into contact with either the thumb or index, the bead immediately deflects away from the hand. Thus, the only information from this point of contact is the confirmation that the hand had reached the bead. Additionally, it is not believed that this is a strategy that is being adopted into the movement. With the highest visual perturbation (i.e., monocular viewing), the percent of errors per subject was 37%. Thus, this cannot be a strategy if it occurs just over a third of the time. Unfortunately, there is no way to confirm these postulations with the results from the current study. Future investigations could implement the use of functional near-infrared spectroscopy (fNIRS) while subjects perform the same task. This would allow us to record changes in blood oxygenation in the respective somatotopic regions responsible for processing tactile and proprioceptive signals

from the upper limbs. With this technique in place, we would be able to determine the degree of neural response associated with these collisions. This would shed some light on whether any information was obtained from the digits regarding information about the target object.

Thirdly, during the initial assessment stage, stereoacuity was assessed using a clinical test (i.e., Randot® Stereotest). This test was in the form of a booklet with large stepwise decreases (e.g., from 800 arcsec to 400 arcsec) in stimuli and there was only one stimulus displayed for each level of stereoacuity threshold. With the small stimulus set, the sensitivity of this test may be limited. Specifically, it is possible that the test did not establish the most appropriate lens to induce the respective stereoacuity manipulations (i.e., the 200 arcsec and 800 arcsec conditions). A significant difference between visual perturbations, for both stereoacuity and visual acuity, is usually double for test-retest repeatability. In other words, within every measurement there is measurement error. For example, a subject may have passed the 200 arcsec stimulus and failed the 100 arcsec stimulus. This would have scored them in the 100-200 arcsec range for a certain lens power. However, if tested again they could have failed the 200 arcsec stimulus. This would place them in the 400-800 arcsec range. In that instance, that particular lens power may have been inducing a level of ~300 arcsec. Therefore, both the large step sizes and the lack of repeatability of this clinical test could have resulted in a slight contamination whereby some lenses that were placed in the 800 arcsec condition could have been more representative of the 200 arcsec condition. Specifically, it is believed that there was an overlap in stereoacuity whereby stereoacuties in the 200 arcsec condition (i.e., 100-200arcsec range) were actually closer to 400 arcsec while stereoacuties in the 800 arcsec condition (i.e., 400-800 arcsec range) were closer to a level of 200 arcsec. Perhaps this contamination was significant enough to influence the results such that no significant difference could be observed between the 200 and

800 arcsec condition. Future studies should incorporate a stereoacuity test that has been programmed on a computer which can allow for several displays of the same stereoacuity threshold in the form of a staircase using the method of limits with several reversals. This would significantly increase the sensitivity of the measure and provide a precise measure of the appropriate lens power to apply to induce the desired perturbation. In all, it is believed that there is a significant difference between viewing at 200 and 800 arcsec of stereoacuity and prehensile performance. The reason this does not appear in the current results is believed to be due to the two stereo manipulations whereby the physical difference between the two manipulations was not large enough to induce a behavioural effect which resulted from a lack of sensitivity in the clinical test used to induce the manipulations. That being said, the results did demonstrate that stereo is involved in the control of grasp force. That is, there was a difference observed between the monocular condition, the 200 and 800 condition, and the binocular condition. There was just no significant difference observed between the 200 and 800 condition.

The fourth limitation is with regards to the task constraints. Interestingly, no effect of visual condition is observed on the peak velocity of the reach phase. Additionally, the results demonstrate an effect of visual condition on the early component of the reach (i.e., the acceleration interval duration). Both of these results are inconsistent with previous literature. This is believed to be due to the nature of the task. That is, previous studies had the target object resting on a table rather than a holder. With the frail holders, the hanging wires of the sensors, as well as the numerous object property manipulations, this may have induced a larger level of caution than in previous studies. This would explain why both early and late components of the reach were prolonged while peak velocity did not change significantly between the conditions. In other words, a more cautious reach was performed resulting in a fixed peak reach velocity to

ensure the hand would not over-shoot the target object and result in a collision. Thus, perhaps the design of the task slightly changed the context of the task and influenced the strategy and safety margin of the motor plan.

Due to a limited budget granted to this study, the force sensors used had a limited capability in comparison to more expensive load cells on the market. Specifically, the Honeywell FSG force sensors only record force in one direction (i.e., 1 degree of freedom). Previous studies (e.g., Flanagan et al., 2003; Johansson and Westling, 1988a) have used load cells which allow for 3 degrees of freedom – i.e., they are capable of recording axial loads. Thus, a more advanced sensor would have enabled the recording and analysis of load forces (i.e., vertical lift forces, parallel to the contact surfaces of the bead) in addition to the grip forces (i.e., perpendicular to the contact surfaces). It is believed that this additional measure would have provided much more insight into the assessment of predictive control of grasping. Specifically, the latency between load force onset and grip force onset could be analyzed to determine whether there are significant differences in lag time between binocular viewing, perturbed stereoacuity, and monocular viewing.

Finally, this study only collected subjects from the university student population. Therefore, subjects were all from a relatively similar demographic. Future studies should investigate into more diverse demographics such as people in the trade industries, developing children, amateur and professional athletes, the older population, and people who have sustained a neurological injury such as a concussion or a stroke. The demographic of the current study was ideal for characterizing the role of stereopsis in fine motor control of the upper limbs, but a few of the other mentioned demographics are groups who may suffer from deficits in binocular

processing and benefit the most from advancements in assessing and treating stereoacuity deficits.

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Appendices

A.1 Waterloo Handedness Questionnaire

Instructions

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

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

1. Which hand do you use for writing?

LA LU EQ RU RA

2. In which hand would you hold a heavy object?

LA LU EQ RU RA

3. With which hand would you unscrew a tight jar lid?

LA LU EQ RU RA

4. In which hand do you hold your toothbrush?

LA LU EQ RU RA

5. With which hand would you pick up a penny off a desk?

LA LU EQ RU RA

6. In which hand would you hold a match to strike it?

LA LU EQ RU RA

7. With which hand do you throw a baseball?

LA LU EQ RU RA

8. With which hand would you pet a cat or a dog?

LA LU EQ RU RA

9. Which hand would you use to pick up a nut or a washer?

LA LU EQ RU RA

10. Which hand do you consider the strongest?

LA LU EQ RU RA

11. Over which shoulder would you swing an axe?

LA LU EQ RU RA

12. With which hand would you pick up a comb?
LA LU EQ RU RA
13. With which hand do you wind a stopwatch?
LA LU EQ RU RA
14. With which hand would you pick up a bat?
LA LU EQ RU RA
15. With which hand would you pick up a piece of paper off a desk?
LA LU EQ RU RA
16. With which hand do you use a pair of tweezers?
LA LU EQ RU RA
17. With which hand would you throw a spear?
LA LU EQ RU RA
18. With which hand would you hold a cloth when dusting furniture?
LA LU EQ RU RA
19. With which hand do you flip a coin?
LA LU EQ RU RA
20. In which hand would you hold a knife to cut bread?
LA LU EQ RU RA
21. With which hand do you use the eraser on the end of a pencil?
LA LU EQ RU RA
22. With which hand would you pick up a toothbrush?
LA LU EQ RU RA
23. With which hand would you hold a needle when sewing?
LA LU EQ RU RA
24. On which shoulder do you rest a baseball bat when batting?
LA LU EQ RU RA
25. In which hand would you carry a briefcase full of books?
LA LU EQ RU RA
26. In which hand would you pick up a jar?
LA LU EQ RU RA
27. With which hand do you hold a comb when combing your hair?
LA LU EQ RU RA
28. With which hand would you pick up a pen?

LA LU EQ RU RA

29. Which hand do you use to manipulate implements such as tools?

LA LU EQ RU RA

30. Which hand would you use to put a nut washer on a bolt?

LA LU EQ RU RA

31. With which hand would you pick up a baseball?

LA LU EQ RU RA

32. Which hand is the most adept at picking up small objects?

LA LU EQ RU RA

33. Is there any reason (i.e. injury) why you do not use the hand you prefer to use for any of the above activities?

YES NO (circle one)

If yes, please explain why you do not use your preferred hand and which activities are affected.

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

YES NO (circle one)

If yes, please explain the special training and which activities are affected.

A.2 Tapply & Bryden Tapping Task

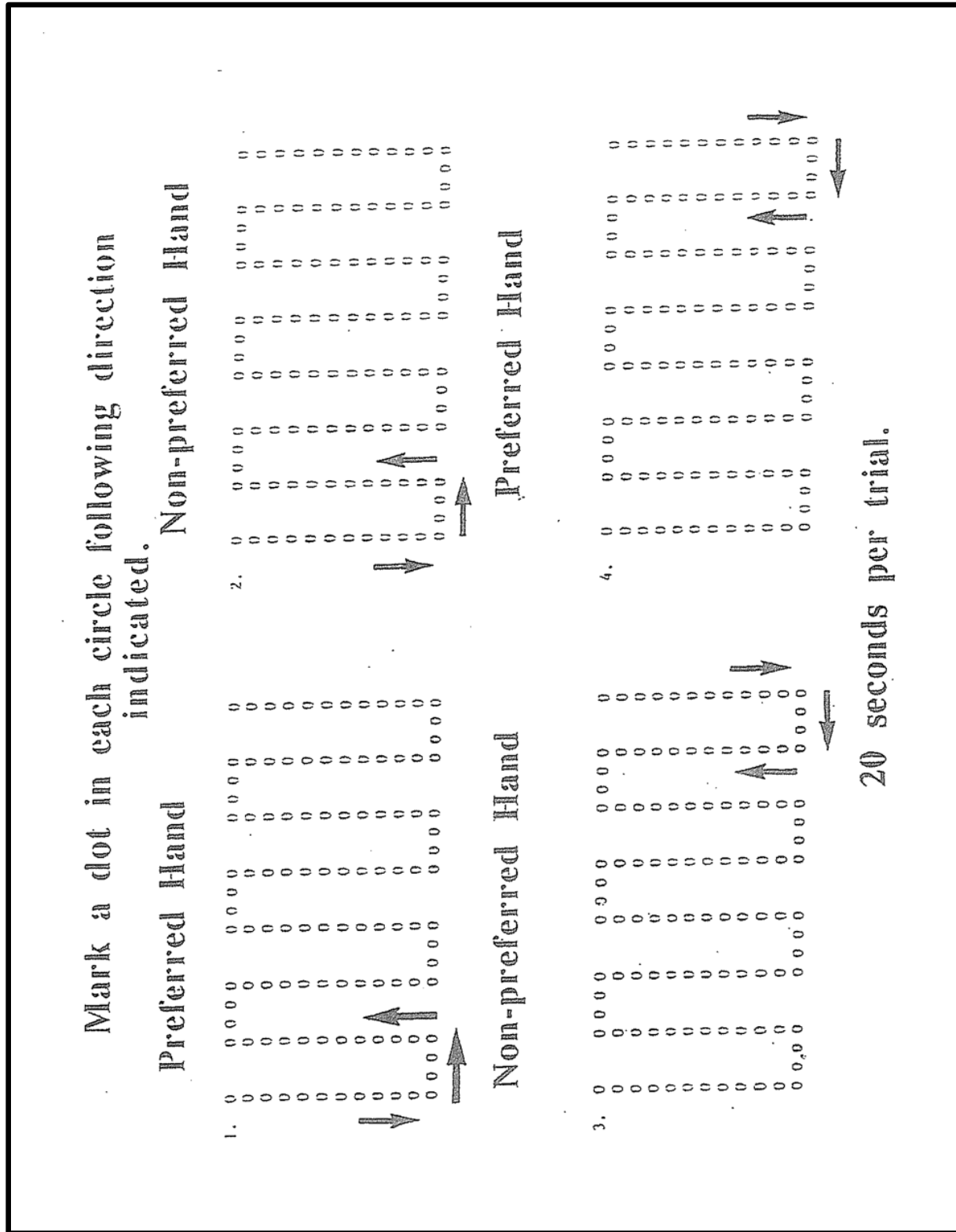


Figure 12. Tapply & Bryden Tapping Task.

A.3 Force Sensor Technical Specifications

FSG Series													
Table 1. Performance Characteristics (At 10 ±0.01 Vdc, 25 °C [77 °F].)¹													
Characteristic	Unit	FSG005WNPB			FSG010WNPB			FSG015WNPB			FSG020WNPB		
		Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.
Force sensing range	N	0 to 5			0 to 10			0 to 15			0 to 20		
Excitation ²	Vdc	3.3	10	12.5	3.3	10	12.5	3.3	10	12.5	3.3	10	12.5
Null offset ³	mV	-30	0	+30	-30	0	+30	-30	0	+30	-30	0	+30
Null shift ⁴ (25 to 0°, 25 to 50° C)	mV	-	±0.5	-	-	±0.5	-	-	±0.5	-	-	±0.5	-
Span ⁵	mV	310	360	395	310	360	395	310	360	395	310	360	395
Linearity (BFSL) ⁶	% span	-	±0.5	-	-	±0.5	-	-	±0.5	-	-	±0.5	-
Sensitivity ⁷	mV/V/N	6.6	7.2	7.8	3.3	3.6	3.9	2.2	2.4	2.6	1.65	1.8	1.95
Sensitivity shift ⁸ (25 °C to 0°, 25 °C to 50 °C)	% span	-	±5.0	-	-	±5.0	-	-	±5.0	-	-	±5.0	-
Repeatability ⁹	% span	-	±0.2	-	-	±0.2	-	-	±0.2	-	-	±0.2	-
Response time (10 %FS to 90 %FS)	ms	-	0.1	0.5	-	0.1	0.5	-	0.1	0.5	-	0.1	0.5
Input resistance	kΩ	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0
Output resistance	kΩ	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0
Plunger deflection	μm	-	31	-	-	40	-	-	51	-	-	63	-
Overforce ¹⁰	N	-	-	15	-	-	30	-	-	45	-	-	60

Notes:

- All force-related specifications are established using dead weight or compliant force.
- The range of voltage excitation which can be supplied to the product to produce an output which is proportional to force but due to ratiometricity errors may not remain within the specified performance limits. Non-compensated force sensors, excited by constant current (1.5 mA) instead of voltage, exhibit partial temperature compensation of span.
- The output signal obtained when the zero force is applied to the sensor. Also known as "null" or "zero".
- The change in the null resulting from a change in temperature. It is not a predictable error as it can shift up and down from unit to unit. Change in temperature causes the entire output curve to shift up or down along the voltage axis.
- The algebraic difference between output signals measured at the upper and lower limits of the operating force range. Also known as "full scale output" or simply "span".
- The maximum deviation of product output from a straight line fitted to output measured over the operating force range. The straight line through a set of points which minimizes the sum of the square of the deviations of each of the points from the straight line.
- The ratio of output signal change to the corresponding input force change. Sensitivity is determined by computing the ratio of span to the specified operating force range multiplied by the supply voltage being used.
- The maximum deviation in sensitivity due to changes in temperature over the operating temperature range, relative to sensitivity measured at 25 °C.
- The maximum difference between output readings when the same force is applied consecutively, under the same operating conditions, with force approaching from the same direction within the operating force range.
- The maximum force which may safely be applied to the product for it to remain in specification once force is returned to the operating force range. Exposure to higher forces may cause permanent damage to the product. Unless otherwise specified, this applies to all temperatures within the operating temperature range.

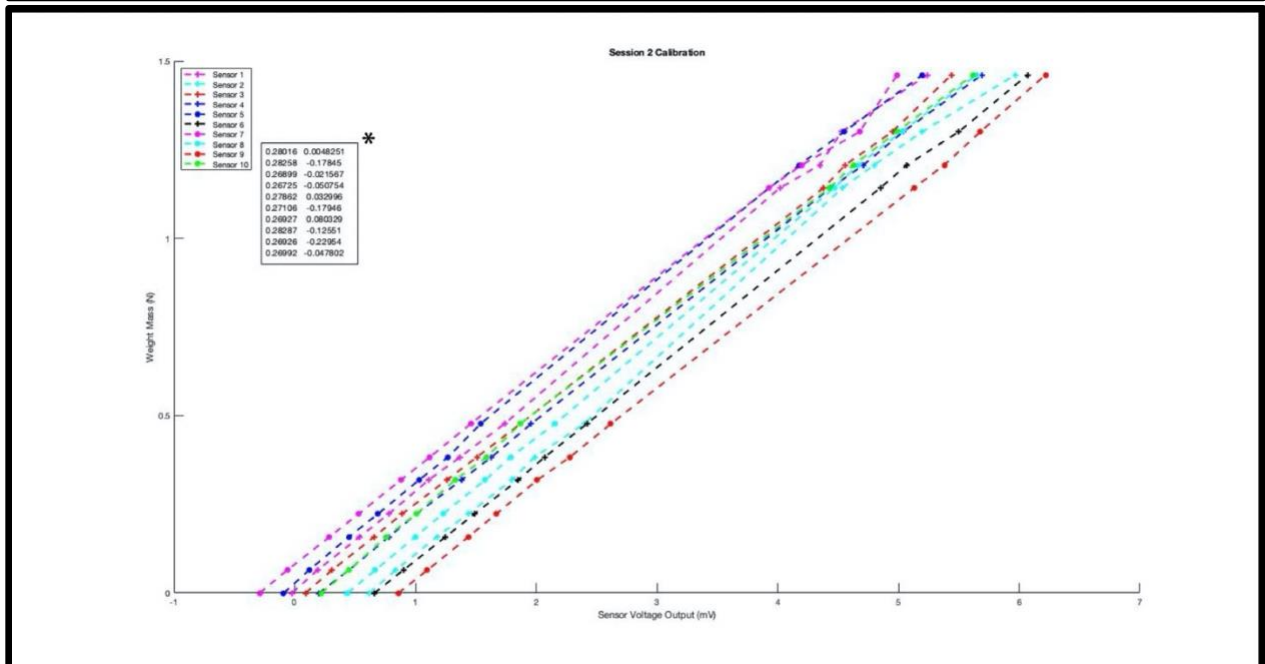
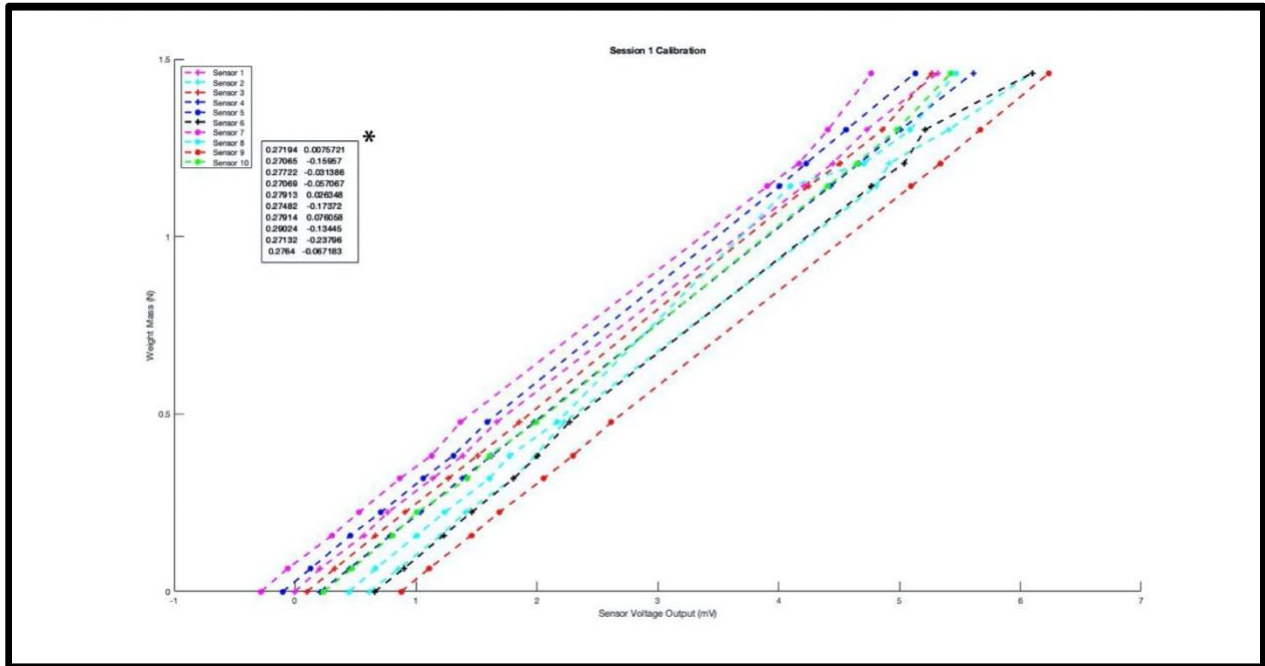
CAUTION
EXCEEDING PRODUCT OVERFORCE RATING

- Ensure the overforce ratings given in Table 1 are not exceeded during any phase of sensor assembly to the board, as well as during the use of the sensor in the application.

Failure to comply with these instructions may result in product damage.

Figure 13. Copy of HoneyWell FSG Series Force Sensor technical specifications table.

A.4 Force Sensor Calibration Curves



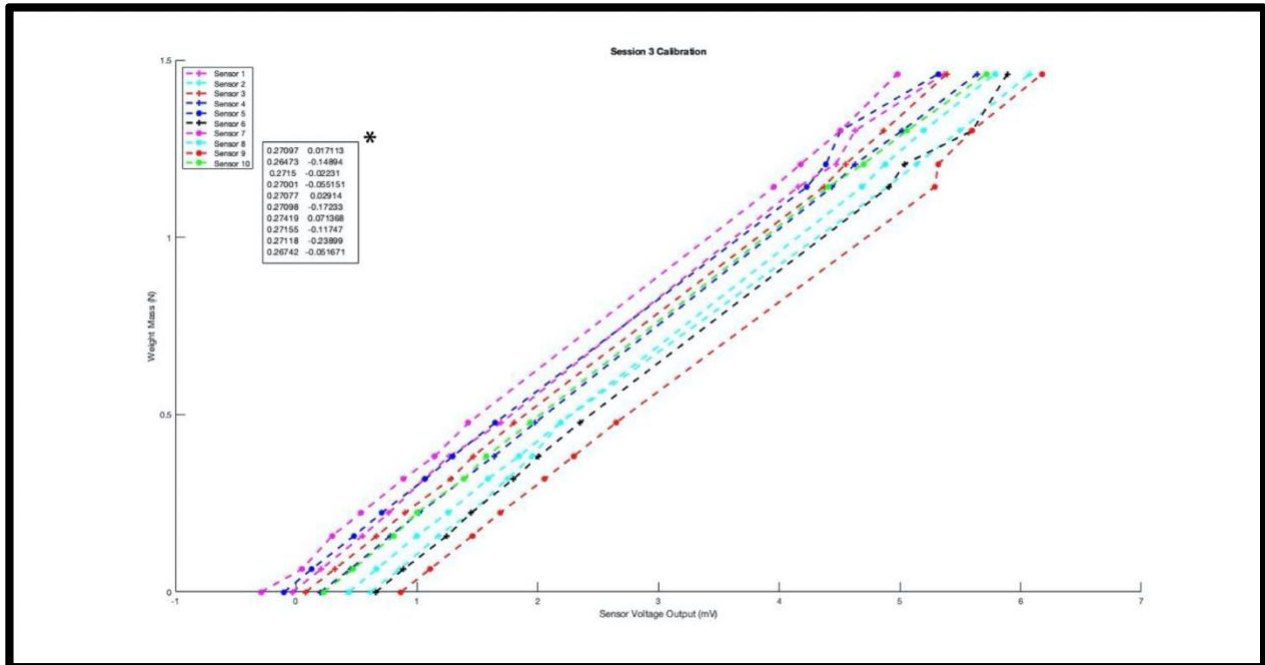


Figure 14. Force sensor calibration curves for three separate days. The textbox highlighted with a “*” includes the inputs to the calibration equations – i.e., column 1: slope, column 2: y-intercept. The rows are respective to the force sensor (e.g., row 3: sensor 3).