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The role of binocular vision in sensorimotor control

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Abstract

Human are adept at avoiding collisions with obstacles in everyday cluttered scenes. Previous studies have uncovered that the visuomotor system accounts for possible obstructions during a reach trajectory, and includes such information into a motor plan to help avoid obstacles. Binocular vision has been shown to provide rich depth information, due to the comparison of images received by each eye. Furthermore, this information has been found to afford advantages during reaching and grasping movements (prehension). However, binocular vision's impact on obstacle avoidance is not well understood. The current study examined binocular vision's role in obstacle avoidance by having participants complete a simple reach to pick up a target object. Also examined was added scene complexity, which provides greater depth information, and its impact upon obstacle avoidance and prehension. It was found that whilst viewing condition did not affect prehensile performance significantly, scene complexity did. That is, binocular and monocular performance was similar on the vast majority of kinematic measures assessed. However, both viewing conditions were significantly affected by more obstacle presented in the scene, with reduced movement duration times, deceleration times, and peak velocity profiles. Motion parallax, as a useful monocular cue, was also examined to determine whether it could be used effectively during obstacle avoidance in a cluttered scene, especially when binocular information was unavailable. The results from experiment 1 and 2 suggest this additional depth information available during cluttered scenes may not be of use when the task is difficult. Furthermore, binocular vision may not be as essential in prehension and obstacle avoidance as was previously thought.

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Declaration

This thesis contains no material which has been accepted for the award for any other degree or diploma in any university and, to the best of my knowledge, this thesis contains no material previously except where due reference is made. I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

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Chapter 1: Introduction

1.1 The visuomotor system and prehension

Vision as a sensory process is not only involved in the creation of internal representations of the outside world, but is also responsible for the planning and control of movements. In fact, vision may have begun as a system for both perception and the control of movements away from the centre of the body (Goodale, 1983, 1996). Goal-directed movements allow us to accomplish tasks in the external environment and vision is instrumental in such accomplishments. The visuomotor system, a coupled sensorimotor structure involving vision and motor control, does not only help us to reach and grasp for objects (prehension) but also allows us to avoid obstacles, dangerous or otherwise, in order to successfully seize an object of interest. People are quite skilled in avoiding collisions with obstacles in everyday cluttered scenes; therefore, the visuomotor system must be a highly efficient system that is adaptable to a changing environment. For example, avoiding collisions with objects on a table with the intent of picking up a water bottle or a cup of coffee are everyday situations we encounter that the majority of us can perform with ease.

In terms of reaching to grasp an object of interest, the hand must be moved to the correct location in space and the hand must also be pre-shaped in accordance with the size, shape and orientation of the object before it is grasped (Jeannerod, 1981, 1984). When an object is reached for and grasped, several visuospatial cues are processed in order to execute the movement accurately. Information about the object's distance from the observer (extrinsic) and its tangible properties (intrinsic) are used to effectively seize the object (Jeannerod, 1981). The visuomotor system encodes both the intrinsic and extrinsic properties of an object and such a distinction allows for a clear picture of the independent, yet coupled nature of prehension. Thus, moving the hand to the correct location refers to the transport component of the reach, and requires extrinsic object information. Whereas, the control of the grip aperture and application of the fingers refers to the grasp component, and this requires intrinsic object information. Although the visual control of the transport and grasp components may be more integrated than originally proposed by Jeannerod (1981), there remains agreement to some sort of functional independence of visuomotor circuits in this area (Chieffi and Gentilucci, 1993; Jakobson and Goodale, 1991).

An important thing to keep in mind is that the weighting of different visual cues for the control of skilled movements, such as reaching and grasping, can differ quite a lot from the way they are weighted for perceptual judgements; however; this is dependent upon the task demands. For instance, Knill (2005) demonstrated that when participants were instructed to place objects on a slanted surface in a virtual world as opposed to making clear judgements about the slanted surface, participants gave much more weight to binocular in comparison to monocular cues. In a similar vein, Servos, Carnahan, and Fedwick (2000) showed that there was a greater reliance by participants upon binocular cues compared with monocular cues when grasping an object, whereas explicit judgements about the distance of the same object were no better under binocular than under monocular viewing. These findings suggest that the coupled approach of the visuomotor system also has an independent component which is tied to the two streams hypothesis first presented by Goodale (1992). This theory posits that vision for action and vision for perception, although closely linked, are processed through differing neural pathways or 'streams'. For example, the *ventral stream* is involved in object recognition and identification in relation to memory, whereas, the *dorsal stream* is involved in processing an object's spatial location in relation to the observer. Eye-hand coordination used for reaching and grasping in particular is mediated by the dorsal stream (Kotecha, et al., 2009), although as noted, both visual pathways are to some extent integrated.

1.2. The nature of obstacle avoidance

Real world settings usually contain cluttered scenes with many objects that may be identified as targets of interest or obstacles to be avoided. As noted, humans are adept at reaching out and grasping target objects, all the while avoiding collisions with non-target objects. Such an observation reveals that we must possess an obstacle avoidance system that encodes potential obstructions and subsumes this information into motor planning (Goodale, 2010). Furthermore, this system modifies the movement of prehension in a subtle and adaptive fashion when obstacles are nearby (Mon-Williams, et al., 2001; Sabes and Jordan, 1997; Tresilian, 1998). Conjectures remains as to whether non-target objects are perceived as obstacles or potential targets for action (Tipper, Howard, and Jackson, 1997). Furthermore, non-target objects may also act as frames of reference that provide additional information used in controlling movements (Diedrichsen, et al., 2004; Obhi and Goodale, 2005). However, it appears that most of the time non-target objects are treated as obstacles inasmuch as the trial-to-trial adjustments of individuals' reach trajectories are highly sensitive to the position of obstacles in depth, height, and along the horizontal plane (Chapman and Goodale, 2008, 2010). This sensitivity captures the conservative nature of the visuomotor system to the extent that the observer's hand and arm usually remain far away from the non-target object regardless of whether it will interfere with the trajectory toward the target of interest.

In recent times, studies have utilized workspace layouts, which include real objects and cluttered scenes, to emulate table-top settings we encounter every day. In this way, the performance of the visuomotor system in ordinary contexts can be examined more closely. Instead of relying upon unnatural scenes with only the target object embedded in the workspace, using naturalistic settings helps to better probe our everyday visuomotor abilities in reaching and grasping. Several studies have utilized these table-top settings to determine how reaching and grasping movements are altered in the presence of non-target objects or 'flankers' (Jackson et al., 1995, 1997; Mon-Williams and McIntosh 2000; Mon-Williams, et al., 2001; Tipper et al., 1997; Tresilian, 1998; Watt and Bradshaw, 2002). These studies have unravelled obstacle avoidance strategies that are also highly conservative in nature. Such anti-collision strategies allows for online control that enables fine spatial and or temporal adjustments to the hand during the movement to change accordingly, and in doing so, the reach trajectory is very different than if the target objects were presented in isolation. Spatially-driven strategies employed in the midst of potential obstacles may include programming a reach that maintains a safe distance from such obstacles (Grant, 2015). Furthermore, in terms of the grasp component, narrowing the peak grip aperture reduces the probability of colliding with possible obstructions (Grant, 2015). A temporal strategy would include slowing down the movement to gain more precise visual feedback; this would be of greater importance at the end phase of the reach (deceleration) and the grasp component, with time being of the essence in successfully adjusting the hand during the final approach toward the object.

1.3. Binocular and monocular vision, and related cues of importance

Binocular vision is considered to be the most important feature in the planning and control of reaching and grasping (Dijkerman et al., 1996; Previc, 1990; Servos et al., 1992; Sakata et al., 1999). Several studies have found that obstructing one eye, and hence removing binocular vision, results in noticeable effects upon prehension. (Keefe and Watt, 2009, Loftus, Servos, Goodale, Mendarozqueta, and Mon-Williams, 2004; Melmoth and Grant 2006, Servos, et al., 1992; Watt and Bradshaw, 2000). With reliance upon monocular vision, participants were slower to reach, had longer periods of deceleration, and performed more online corrections during the overall reach trajectory and especially during the closing grip phase of the reach. However, we should suspend our judgement of monocular vision for the moment, because monocular cues still create an allowance of depth perception and thus remain reasonably useful in the programming and control of prehension. For instance, Marotta and Goodale (1998, 2001) demonstrated that monocular cues (familiar object size, height in the visual field, occlusion, etc.) can be effectively used to control grasping movements. Although, the reliance upon these cues seems to reduce considerably when binocular cues are available. That is to say, binocular cues may outweigh the use of monocular cues because the former are more readily accessible and afford more precise depth information (McKee and Taylor, 2010). In contrast, monocular cues appear to provide less visual certainty, and inaccurate information may therefore ensue. This is because monocular cues rely upon the changes of objects along the x-axis, whereas binocular vision allows for vision along the depth or z-axis as well as the x-axis (McKee and Taylor, 2010).

As noted earlier, both intrinsic and extrinsic object properties are given by a number of different visual cues in ordinary scenes. Yet, there are two visual cues in particular that operate to provide accurate and reliable depth information. These are binocular disparity and motion parallax and are highly important when prehension is concerned. These cues can provide the absolute metric properties including distance and shape of objects, once suitably scaled (Watt and Bradshaw, 2000). In comparison, other visual cues available (such as interposition, height in the visual field, texture gradient, linear perspective, etc.) can provide only relative depth information (Watt and Bradshaw, 2000). Due to the fact that binocular disparity and motion parallax can offer accurate extrinsic and intrinsic object properties, they are of great importance in reaching and grasping control. Although one should not underestimate vergence as a binocular cue, as it can provide important depth information to an observer, such a cue becomes much less useful when perceiving objects 40 cm onwards due to distance underestimation, unlike binocular disparity (Howard, 1995).

1.3.1. Binocular disparity and its importance in prehension

Binocular disparity refers to the difference in a visual image due to the lateral separation of the two eyes. The interpupillary distance between the left and right eye is approximately 6cm and due to the fact that they are separated in space, it is no surprise that two different views of the external world result. As there are two sources of visual information, around where the eyes are fixating, a fusion of monocular images (binocular fusion) takes place in a small volume of visual space (Schaadt, et al., 2013). This is because a portion of the two visual fields corresponding to the two eyes overlap and combine to form a ‘cyclopean’ image. Because of this provision of rich visual information, binocular disparity allows for accurate depth perception regarding the shape and size of an object. As discussed, such a powerful cue can only exist with the use of two eyes, and the information extracted from this operation is processed by the visuomotor system, which can be used for precise grasping movements (Bingham, et al. 2001; Mon-Williams and DIjkerman, 1999; Rogers and Caganello, 1989; Servos, Goodale, and Jakobson, 1992; Watt and Bradshaw, 2003). Neurophysiological evidence also intimates that binocular disparity is essential in prehensile control.

For example, studies have shown that disparity-sensitive cells in the posterior parietal cortex, being involved in physical control and manipulation activities, are selective for three-dimensional surface orientation, along with three dimensional axis orientation (Sakata, Taira, Kusunoki, Murata, & Tanaka, 1997; Sakata, et al. 1998, 1999; Shitaka, Tanaka, Nakamura, Taira, & Sakata, 1996).

Although it is well understood that two eyes are always better than one in affordances of depth information, particularly because of binocular disparity (an important binocular cue leading to stereopsis), findings disagree upon the components of the reach and grasp movement that are enhanced due to binocular vision and the magnitude of this enhancement. Some studies have demonstrated that binocular vison increases the performance of planning and online control of the both the reach and grasp. For example, Servos et al. (1992) found that binocular movements were planned and executed faster than when only relying upon the dominant eye. Furthermore, participants in the monocular condition took longer to reach, and peak deceleration was increased as opposed to the binocular condition. Lastly, in terms of pre-shaping their hands, participants made smaller grip apertures when attempting to grasp objects under monocular viewing. Grip aperture refers to the spacing between the thumb and forefinger, and is important to consider because it is affected by the amount of visual information presented in a scene and perhaps the clutter of the scene. Servos et al. (1992) interpreted these above results as a tendency for participants to underestimate the intrinsic and extrinsic properties of the target object due to a lack of binocular information during programming of the movement. However, Jackson et al. (1997) found no difference between viewing conditions in reaching and grasping a single object in a cue enriched workspace. Though, this study used the same object at an unchanging distance throughout, which could have increased object familiarity and thus improved monocular performance. This could occur because feedback about actual distance is attained from proprioceptive information arising due to the extent of the reach, and the hand's position relative to the target. If done enough times, a participant will possess a highly accurate motor plan of the scene, and the significance of detailed cues available for action will diminish.

Watt and Bradshaw (2000) made similar discoveries as above, wherein no differences between binocular and monocular viewing in terms of the movement onset time or to the early phase of the reach were found. Notwithstanding this fact, they did find a binocular advantage in relation to the programming and execution of the grasp. Verghese (2016) also found a correlation between grasp performance and stereoacuity, concluding that individuals stricken with central field loss would benefit from stereopsis. Although especially useful during the grasping of an object, it appears that binocular vision may not be essential in executing an accurate hand movement such as a reach or during pointing. For instance, Ma-Wyatt, McKee, and Verghese, (2004) demonstrated that there was no difference between binocular and monocular viewing in guiding accurate pointing movements when dots appeared in the frontoparallel plane. However, they reported that binocular information was important for obstacle avoidance. With regards to the end phase of the reach during prehension, Watt and Bradshaw (2000) found that participants pre-shaped their grip to a wider peak aperture under monocular viewing rather than to a smaller aperture as found by Servos et al. (1992). Watt and Bradshaw (2000) argued that the removal of binocular viewing degrades important spatial information processed by the visuomotor system about the object. This is in opposition to earlier theories that argued for a systematic bias of distance and size estimates under monocular viewing. By obstructing one eye, either by an eye patch or shutters, stereopsis (depth perception from binocular disparity) is removed, thus reducing the amount of depth information. However, the extent of depth information removed under monocular vision, and its impact upon prehension and obstacle avoidance is in need of clarification. Although it was previously thought that binocular vision was critical in accurately executing goal-directed actions, this has been questioned more recently (Ma-Wyatt, McKee, Verghese, 2004; Watt and Bradshaw, 2000, 2002).

1.3.2. Motion parallax and its importance in prehension

Although not as well understood as binocular disparity with regards to prehension, motion parallax is a monocular cue that involves horizontal and vertical movements of the head. This self-induced head motion allows the observer to apprehend different viewpoints of a scene with one eye, and hence significant depth information can be acquired. Thus, under circumstances where one eye is relied upon, motion parallax may be an important visual cue (Marotta, Kruyer, and Goodale, 1998; Marotta, Perrot, Nicolle, and Goodale, 1995; Marotta, Perrot, Nicolle, Servos, and Nicolle, 1995). A study by Marotta, Perrot, Nicolle, Servos, and Goodale (1995) looked at head movements generated naturally between long-term enucleated patients (a patient with one eye surgically removed) and normal-sighted controls during prehension. No differences were found in normal observers between head movements under binocular or monocular viewing. In contradistinction, the enucleated patients made larger and faster head movements to overcome the reduced information under monocular viewing. The authors contended that the enucleated patients had learned to use the information from motion parallax due to their condition, whereas normally-sighted observers were not aware of such strategies. An important feature of motion parallax is that is has been shown to contribute more to the calculation of reach distance than the grasping component, and it may only be of importance when binocular cues are not available (Marotta, Kruyer, and Goodale, 1998; Watt and Bradshaw, 2003). Marotta, et al. (1998) found that while restricting head movements under binocular viewing did not affect reaches, the restriction of head movements under monocular viewing increased the amount of online corrections of the reach. This indicates that with the inclusion of motion parallax under monocular viewing, the performance of reaching and grasping may be enhanced. Yet it remains unclear whether self-generated head motion is enough to provide useful object and scene information to be used in the control of such movements. Although motion parallax is a useful cue to depth under monocular viewing, it is undecided whether the coupling of one eye and self-generated head motion can approach reaching and grasping performance reminiscent of binocular viewing.

Adults with binocular deficiencies from amblyopia, due to a lack of correspondence between the two eyes, have also been shown to exhibit slower and less accurate grasping movements (Melmoth, et al., 2009). Be that as it may, those who have this condition appear to be as fast as those normally-sighted individuals using two eyes in executing the reach. This is because amblyopes learn to use this self-generated head motion in both lateral and vertical directions to accommodate their condition, and the degree of adeptness increases as a function of the time elapsed since the reduction of their stereopsis (Marotta, Perrot, Nicolle, and Goodale, 1995). Overall, amblyopia increases the uncertainty about the location and properties of an object along the line of sigh. The problem is that monocular vision alone is not able to compensate for such reduced visual information (McKee and Taylor, 2010). Thus, in terms of the grasp component, those with amblyopia will show accuracy deficiencies and slower peak deceleration and terminal phase grasping compared with those with functioning stereopsis. A solution to this problem is for the amblyope to move around the object, which allows the z-axis information to be converted into x-axis information. The only problem with such as strategy is that this takes time and it is only effective for close objects. Individuals suffering from visual field loss due to glaucoma also exhibit similar patterns of behaviour in terms of self-induced head motion (Fortenbaugh, et al., 2007; Kotchea, et al., 2009). In this case, glaucoma patients have reduced aspects of spatial vision and therefore have impairments in either transport or grasping components. If it is the case that individuals with binocular deficiencies begin to use motion parallax to accommodate their condition, and that they can perform reaches that are just as accurate as normal sighted people, then motion parallax must be a highly important cue to depth when stereopsis is unavailable. In the current study, it will be determined whether motion parallax will help participants under monocular viewing perform better than if no head motion was permitted. Moreover, will the performance in reaching and grasping with the inclusion of motion parallax under monocular viewing be comparable to performance under binocular viewing?

1.4. The aim of the study

The present study aims to determine the contribution of binocular vision in reaching and grasping movements when obstacles are present. The task involved instructing participants to reach rapidly toward a target object and to grasp it. In different conditions, additional objects were introduced that acted as obstacles and also as reference frames, providing additional information about the depth of the target object relative to the participant. Each participant was tested under both binocular and monocular conditions. In the first experiment, participants reached and grasped target objects embedded in three different workspace layouts. These layouts corresponded to different levels of scene complexity. More cluttered scenes involved avoiding collisions with obstacles that obstructed the hand's path toward the target object. In the second experiment, a cluttered scene was used to determine whether motion parallax aided in accomplishing the prehensile task, also relative to viewing condition.

In comparing viewing conditions during a prehensile task, general performance pertaining to kinematic measures such as movement duration, peak acceleration, peak velocities, and obstacles knocked over, will be assessed, all the while focusing upon when during the movement (i.e. the early phase or end phase of the reach) binocular vision confers the most advantages, if any, and also what width the grip aperture assumes amid these obstacles. These last two considerations will be examined closely due to the competing results that previous studies have found. Another important feature of the study is to further examine the obstacle avoidance capabilities of the visuomotor system while taking into consideration scene complexity. This consideration was included to determine how varying amounts of visual information embedded in a scene may influence the performance of prehension and obstacles avoidance.

In their study on depth judgements in natural settings, McKee and Taylor (2010) used an austere setting, which included a number of monocular cues, and later enriched the setting by adding objects to mimic the normal clutter of everyday table-top scenes (including texture gradients and occluded objects). They found that while monocular thresholds improved when the scene was more cluttered, binocular thresholds remained superior throughout both scenes. The improvement in monocular thresholds occurred because object clutter provided more depth information. The current study wanted to determine whether an enriched setting that included more visual information in the form of clutter, would increase reaching and grasping movements under monocular viewing in contrast to binocular viewing. As discussed, the weighting of visual cues for perceptual judgements and for goal-directed movements must not be ignored.

In the current study, the workspace was raised in an attempt to enhance the importance of binocular depth cues in performing the prehensile task. This is somewhat in contradistinction to studies where the target objects can be seen from above and participants are able to attain a two-dimensional plan of the workspace layout, as noted by Verghese, et al., (2016). In such a case where an above plan of the layout is attained, the role of binocular vision in prehension is more difficult to determine, especially in relation to grasping performance, not to mention obstacle avoidance. With regards to object placements, target objects will be randomized, positioned at the same distance but differing in lateral position, so that familiarity with reach trajectory per trial will be more difficult to achieve.

1.4.1. Experiment 1

To begin with, the first experiment will compare the overall performance between binocular and monocular vision in prehension. Furthermore, the performance of obstacle avoidance will be assessed by including a number of obstacles in several layouts. Three different workspace layouts will be presented to participants – these corresponded to difficulty levels. Thus, the greater the difficulty level, the more complex the layout, and thus the richer the visual scene. In increasing the scene complexity over the course of experiment 1, it will be determined if the integration of monocular cues can be compared to the use of binocular cues during prehension and obstacle avoidance.

In the most cluttered scene, the inclusion of several obstacles and occluded objects behind the targets will also allow for greater disparity gradients. That is, by having a richer and busier environment, there should be a greater amount of binocular information available from the differences in spatial points that arise due to the two different views of objects in each eye. Does an increase in the disparity gradient in the cluttered scene improve performance using binocular vision, or will the more difficult-to-navigate scene, although richer in depth information, be comparable to using monocular vision?

1.4.2. Experiment 2

As for the second experiment, motion parallax as a highly useful monocular cue will be included in the presentation of the most cluttered scene. That is, participants will be free to make lateral head movements to determine whether this cue will add an advantage during prehension and obstacle avoidance. As indicated, motion parallax may only be of use when binocular vision is unavailable; however, participants will still be tested using motion parallax during both viewing conditions to determine if this was in fact the case. Additionally, it will be examined whether prehensile performance using monocular vision with motion parallax can compare with binocular vision without motion parallax.

1.4.3. Hypotheses

It is hypothesized that binocular vision will lead to increased performance on the prehensile task. Participants should take less time to make contact with the target, should have reduced movement duration, and should not reduce their velocity (deceleration time) at the end phase of the reach as significantly as under monocular viewing.

With regards to the grasp component, participants using monocular vision should action a narrower grip aperture to combat positional uncertainty that results from the use of one eye in the context of confined spacing between obstacles in scene 2 and 3. Perhaps in the impoverished scene wider grip apertures are assumed under monocular viewing due to positional uncertainty.

With regards to obstacle avoidance, it is hypothesized that due to the uncertainty of depth judgements when using monocular vision, participants should knock over more obstacles under monocular viewing that under binocular viewing.

It is hypothesized that increased scene complexity will lead to longer movement duration times, extended peak velocity to end times (deceleration time), and more obstacles being knocked over, regardless of viewing condition. Furthermore, increased scene complexity will produce narrower grip apertures to accommodate the confined space between obstacles in both viewing conditions.

During experiment two, the use of motion parallax should increase prehensile performance using monocular vision over monocular vision with no motion parallax, including reduced movement latency and movement duration times. However, as per past research, no changes in prehensile performance using binocular vision combined with motion parallax should be evident.

Chapter 2: Method

2.1. Participants

Eight adults aged between 18 and 41 years volunteered to participate in the study. All participants had normal or corrected-to-normal vision and, with the exception of two observers, were naïve to the purpose of the experiments. All participants were tested for stereoscopic using the Randot Stereo Test and had intact stereoscopic vision. The participants had no history of visual motor deficits. Hand preference was determined using the Edinburgh Handedness Inventory (Oldfield, 1971). Only two participants were left-handed. The experimental procedure was approved by the Adelaide University Ethics Committee. Furthermore, participants were free to withdraw their consent at any time during the experiment.

2.2. Apparatus

Experimental layouts were set up on a matte black table. A platform was used on a part of the table (58 X 36 cm across), raising the workspace 10 cm above the height of the table. All stimuli were placed in this area. The workspace was raised to increase the importance of binocular depth cues by lessening the view of objects from above. The participant rested their chin on a chin rest that was fixed to the table and reduced head movement. The height of the chin rest was for each participant so that his or her eye was exactly 30 cm above the platform. The starting position of the participant's hand was a mouse that acted as a start button. The mouse was mounted on the platform.

Hand movements were tracked using a Polhemus Liberty electromagnetic motion tracking system at a sampling rate of 240 Hz with the static accuracy of 0.8 mm RMS for the x, y, z position, which returned information about hand position. A Polhemus sensor was attached to the forefinger and thumb of the participant's dominant hand with a custom Velcro glove. This glove was also fastened around the participant's wrist. Custom software written in Matlab was used for each experiment. This software was used to randomize the conditions and to acquire and store data from the hand tracking system for each trial.

2.3. Targets

The target objects were small wooden colour-coded cubes (2.5 X 2.5 cm) that were placed 25 cm from the start button. Target object positions differed laterally with a spacing of 5 cm between each object. The middle target object was exactly central to the midline, which was also aligned with the start button. The obstacles used were cylindrical glue sticks (3 cm X 3 cm) 10.5 cm tall. The positions of these obstacles differed depending upon the difficulty of the layout.

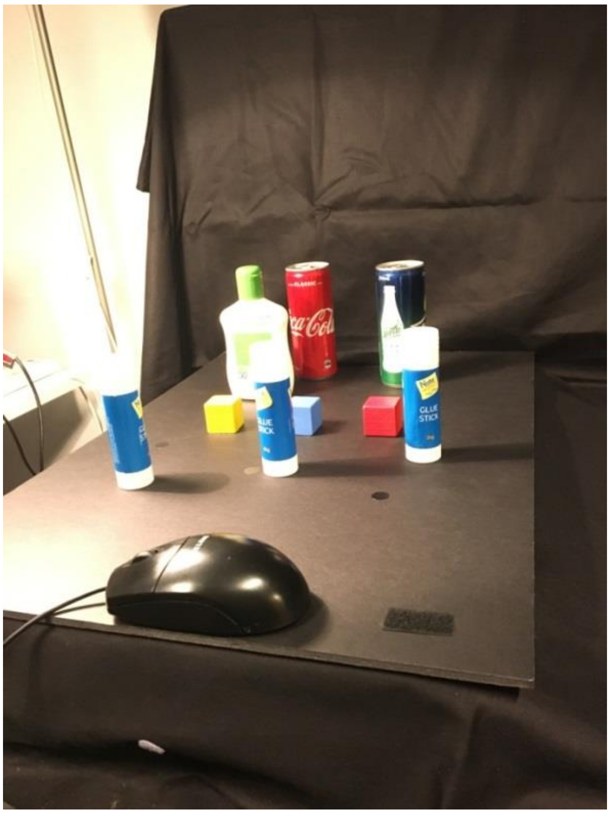

Figure 1. Experimental setting.

This is the cluttered scene (scene 3), which includes three obstacles that participants have to avoid whilst reaching and grasping the colour-coded target objects. Furthermore, soda cans and a sun screen bottle were used as occluded objects, presenting increased depth information to observers. The mounted mouse acted as the start button to begin the trial.

Normal ceiling lighting illuminated the room. The workspace layout was further illuminated by a lamp that was positioned to shed light upon the table-top scene. This was done to improve the clarity of the visual scene and to enhance the monocular cue of shadowing.

2.4. Design

A repeated measures within subjects design was used for each experiment. In experiment 1, participants made reaches under both binocular and monocular viewing conditions with the fixed chin rest preventing head motion. In experiment 2, participants made reaches once again in both viewing conditions, but this time head motion was allowed by removing the chin rest. Participants completed 6 blocks of 15 trials (3 blocks per viewing condition) in experiment 1, and 2 blocks of 15 trials (1 block per viewing condition) in experiment 2. This equated to a total of 120 trials per participant. The order of all blocks was counterbalanced.

Each block in experiment 1 consisted of a varying layout complexity. That is, the amount of obstacles and visual information availability increased with scene complexity. These layouts corresponded to three difficulty levels (impoverished, more complex, and cluttered). The first scene consisted of an impoverished scene wherein only the target objects were present. This isolated layout was used to obtain a baseline marker for prehensile performance. Scene two consisted of an increased difficulty level whereby two obstacles were included in the layout, increasing the availability of visual cues. Lastly, scene three was more cluttered, consisting of three obstacles and additional objects behind the targets to enhance the disparity gradient, the monocular cues available, and to further mimic the normal clutter of a table-top setting. During experiment 2, only the cluttered scene was examined to determine the effects of motion parallax against no motion parallax. It was unnecessary to analyse the effects of motion parallax against all three layouts, because the aim of experiment 2 was to examined whether numerous monocular cues (including motion parallax) provided in scene 3, would improve monocular relative to binocular performance.

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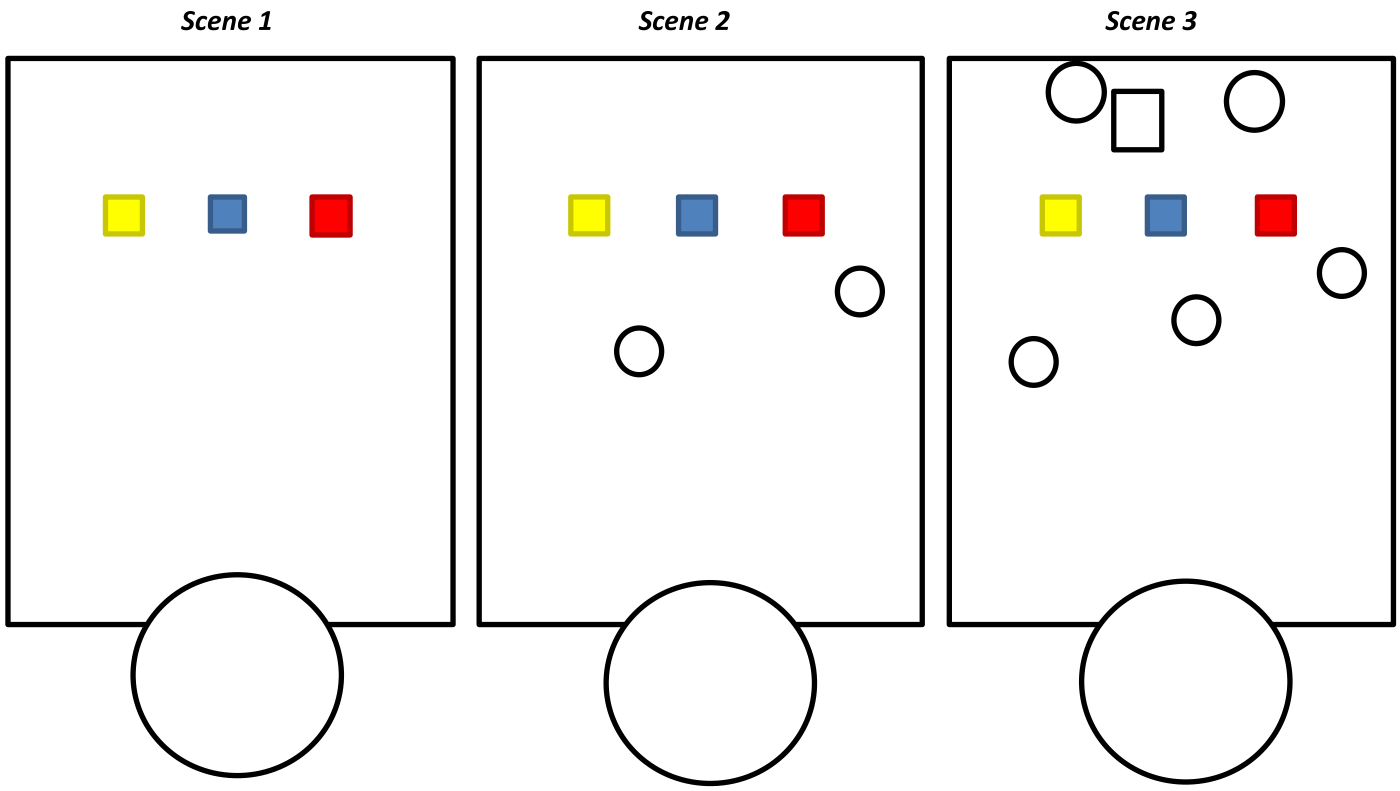

Figure 2. Scene complexities and object placements

Basic schematic of the layout of different scene complexities and the object placements of those scenes. Scene 1 – impoverished, scene 2 – more complex, scene 3 – cluttered. Participants (represented by the large circle) were seated and their head was fixed to the table-top by a chin rest in experiment 1. The chin rest was removed during experiment 2, as participants were permitted to generate lateral head motion. The coloured cubes were the target objects that participants were instructed to reach and grasp. The circles between the participant and the target objects were the obstacles (glue sticks). Additional objects behind were ordinary household objects that increased depth information, to be used in the control of prehension and obstacle avoidance.

2.5. Procedure

Participants were instructed to make quick and accurate reaches with their dominant hand. They were further explicitly instructed to pick up the target objects with their thumb and forefinger only. Participants were to with their forefinger press the mouse, which acted as the start button. Data began to be obtained as soon as participants dislodged their forefinger from the start button. The fitted hand tracking sensors calculated a wealth of kinematic measures.

On each trial, a verbal command was given to instruct participants as to which coloured target object to reach and grasp. Next, an audible beep (randomized to sound between 0.5 and 1 s) signified the beginning of the trial and informed participants to ready themselves and to press and hold the start button with their forefinger. A second beep followed, which was the cue to release the start button and reach for the target object. After a 1 sec fixed interval, a third beep signalled the end of the trial. If a participant took too long to pick up the target object before the third beep sounded, the trial was discarded. As described above, each participant completed 6 blocks for experiment 1.

Experiment 2 incorporated head motion and hence freed participants from the fixed chin rest. Participants were instructed to make smooth lateral head movements of about 5 – 10 cm either side of their midline. A metronome was used to guide participants' head movements at 1Hz by an audible tone. The metronome sounded during the entire block so that participants' head movements were rhythmically guided and thus consistent. As per Watt & Bradshaw (2002), participants were instructed to continue making lateral head movement during reaches only if they wished, due to the difficulty involved in reaching accurately when making movements of the head. The order of experiments was counterbalanced.

2.6. Dependent measures

The performance of participant's programming and online control of the reach alongside the grasping of the target object were examined using a variety of kinematic measures. All kinematic data were low-pass filtered at 20Hz with a two-way 4th order Butterworth filter. Movement latency was defined as the time between start button release and velocity, and movement duration was defined as the time from movement onset to movement end (target object contact). These two general kinematic measures were computed for each trial to determine the performance of the overall planning and execution of the reach. Peak acceleration was defined as the maximum velocity executed during the early phase of the reach. Peak velocity was defined as the maximum velocity executed during the entire reach. Time to peak acceleration was defined as the duration between movement initiation (the release of the mouse button) and peak acceleration. Time to peak velocity to end was defined as the duration between peak velocity and touch response, or simply the deceleration time. These several measures defined above relating to velocity and acceleration profiles correspond to the reach dynamics of the transport component and were calculated for each trial. Mean grip aperture was defined as the maximum aperture between the thumb and forefinger before object contact. Additionally, time to mean grip aperture was defined as the duration between movement initiation and the pre-shaping of the hand in response to the target object. These two measures above were calculated to examine the grasp component on any given trial.

Chapter 3: Results

The data were analysed by a repeated measures analysis of variance (ANOVA) using R. The main effect of viewing condition and scene complexity were computed in experiment 1. Planned contrasts were assessed using a repeated measures analysis of variance design, to determine the relationship between binocular and monocular viewing and the relationship between different scene complexities. Individual means and the average SEM for each dependent measure were calculated for each viewing condition and scene complexity.

3.1. Experiment 1

Table 1 illustrates the overall performance on the prehensile task relative to viewing condition, with the data from all three scenes collapsed into a single value. Table 2 further illustrates the overall performance relative to viewing condition, but includes average performance for each individual scene.

[redacted]

Table 1.
Summary of mean values and standard error of the means (SEM) in parentheses for binocular/monocular viewing across all scenes.

Dependent measure	**Viewing condition**	
	Binocular	Monocular
Movement latency (ms)	261.5 (16.4)	249 (9.3)
Movement duration (ms)	644.5 (20.7)	678.7 (22.4)
Peak acceleration (cm/s^{-2})	582.6 (90.7)	550.3 (80.1)
Peak velocity (mm/s)	133.4 (5.5)	131.1 (4.4)
Time to peak acceleration (ms)	109.6 (7.6)	101.3 (8.3)
Time to peak velocity from start (ms)	212.2 (7)	215 (8.1)
Time to peak velocity to end (ms)	431.8 (20.3)	473.8 (26.1)
Mean grip aperture (mm)	9.4 (0.16)	9.6 (0.19)
Time to mean grip aperture (ms)	477.2 (21.3)	482.3 (20.3)

Table 2.
Summary of mean values and SEM in parentheses for binocular/monocular viewing for each individual scene.

	Scene complexity					
	1		2		3	
Dependent measure	**Viewing condition**					
	Binocular	Monocular	Binocular	Monocular	Binocular	Monocular
Movement latency (ms)	253.9 (25.6)	255.6 (18.4)	261.3 (31.7)	246.4 (17.1)	269.3 (30.7)	245 (15)
Movement duration (ms)	544.2 (26.2)	580.6 (24)	683.9 (24.9)	715.2 (33.3)	705.6 (26.7)	740.2 (33.3)
Peak acceleration (cm/s^{-2})	616.2 (184.7)	454.1 (59)	666.6 (204.1)	465.4 (57.7)	465.1 (47.5)	731.3 (225.4)
Peak velocity (mm/s)	157.7 (10.4)	145.5 (7.1)	121 (5.2)	121.7 (5.8)	121.4 (5.7)	126.2 (8.1)
Time to peak acceleration (ms)	120.9 (17.2)	125 (18.1)	105.9 (13.2)	89.4 (8.1)	102 (8.3)	89.4 (13.1)
Time to peak velocity from start (ms)	227.6 (12.4)	235 (9.6)	204.7 (11.4)	203.8 (14.8)	204.2 (12)	206.3 (15.7)
Time to peak velocity to end (ms)	316.5 (16.8)	344 (21.8)	477.4 (19.1)	543.6 (43.2)	501.4 (22.7)	533.8 (28)
Mean grip aperture (mm)	10.2 (0.3)	10.4 (0.4)	9.1 (0.2)	9.3 (0.2)	8.9 (0.1)	9 (0.1)
Time to mean grip aperture (ms)	374.1 (18.1)	397.3 (20)	501.8 (25.7)	516.6 (27.1	555.7 (31.6)	532.9 (36.8)

3.1.1. Transport component

The transport component consists of the kinematic measures peak acceleration, peak velocity, time to peak acceleration, and both time to peak velocity from start and to end. Table 3 illustrates that there was a significant main effect of viewing condition upon time to peak velocity to end (F (1, 7) = 9.14, p < 0.05), with participants spending longer between peak velocity and the end of the reach (making contact with the target) under monocular viewing. There were no other significant main effects of viewing condition upon the transport component. Mauchly's test of sphericity for peak acceleration's block factor ($W = 0.01$, $p = 0.00$) and peak velocity's block factor ($W = 0.32$, $p = 0.03$) were violated. Greenhouse-Geisser corrections were thus used for peak acceleration ($e = 0.94$, *Pr(> F [GG]* = 0.05) and peak velocity ($e = 0.67$, *Pr(> F [GG]* = 0001). As can be seen from table 1 and 2, it took participants slightly longer on average to complete the prehensile task, as participants spent more time in the end phase of the reach under monocular viewing. Surprisingly, the presence of more obstacles and thus greater scene complexity did not afford noticeable advantages for binocular vision.

Table 3.
Summary of the main effect of viewing condition, scene complexity, and the interaction term for each dependent measure relating to the transport component.

Dependent measure	**Main effect of viewing condition**			**Main effect of scene complexity**			**Viewing condition x scene complexity interaction**		
Peak acceleration (cm/s^{-2})	$F(1,7) = 0.34$	$p = 0.57$	n/s	$F(1,14) = 3.93$	$p < 0.05$		$F(1,14) = 0.34$	$p = 0.31$	n/s
Peak velocity (mm/s)	$F(1,7) = 1.21$	$p = 0.31$	n/s	$F(1,14) = 22.62$	$p < 0.001$		$F(1,14) = 3.31$	$p = 0.16$	n/s
Time to peak acceleration (ms)	$F(1,7) = 0.99$	$p = 0.35$	n/s	$F(1,14) = 2.43$	$p = 0.12$	n/s	$F(1,14) = 0.57$	$p = 0.12$	n/s
Time to peak velocity from start (ms)	$F(1,7) = 0.32$	$p = 0.58$	n/s	$F(1,14) = 9.25$	$p < 0.01$		$F(1,14) = 0.17$	$p = 0.83$	n/s
Time to peak velocity to end (ms)	$F(1,7) = 9.14$	$p < 0.05$		$F(1,14) = 23.15$	$p < 0.001$		$F(1,14) = 0.69$	$p = 0.51$	n/s

There was a significant main effect of scene complexity on movement duration ($F(1, 14) = 24.48$, $p < 0.001$) and several components of the reach dynamics including peak acceleration ($F(1, 14) = 3.93$, $p < 0.05$), peak velocity ($F(1, 14) = 22.62$, $p < 0.001$), time to peak velocity from start ($F(1, 14) = 9.25$, $p < 0.01$), and time to peak velocity to end ($F(1, 14) = 23.15$, $p < 0.001$), as can also be seen in table 3. With regards to movement duration, planned contrasts demonstrated that there was a significant difference between scene 1 and 2 ($t(1, 14) = -5.54$, $p < 0.0001$) and between scene 1 and 3 ($t(1, 14) = -6.48$, $p < 0.0001$), with participants taking longer to complete the prehensile task as scene complexity increased. Additionally, in terms of peak velocity, planned contrasts demonstrated a significant difference between scene 1 and 2 ($t(1, 14) = 6.06$, $p < 0.0001$) and scene 1 and 3 ($t(1, 14) = 5.56$ $p = 0.0001$), with a reduction in peak velocity with increased scene complexity. Furthermore, planned contrasts showed that there was a significant difference in time to peak velocity from start between scene 1 and 2 (t (1, 14) = 3.79, $p < 0.01$) and scene 1 and 3 (t (1, 14) = 3.66, $p < 0.01$), with a reduction in the measure as scene complexity increased. In terms of time to peak velocity to end, planned contrasts illustrated a significant difference between scene 1 and 2 (t (1, 14) = -5.78, $p < 0.0001$) and scene 1 and 3 (t (1, 14) = -6.01, $p < 0.0001$), with an extended end phase occurring with added scene complexity. With regards to peak acceleration, planned contrasts illustrated that there was only a significant difference between scene 1 and 3 (t (1, 14) = -2.8, $p < 0.05$), with peak acceleration increasing with scene complexity. No significant interactions between viewing condition and scene complexity for the transport component were found.

3.1.2. Grasp component

There was no significant main effect of viewing condition upon grip aperture and time to mean grip aperture as shown in table 4. Furthermore, planned contrasts demonstrated that there was no significant difference between viewing conditions for the grasp component. There was a significant main effect of scene complexity on mean grip aperture (F (1, 14) = 33.13, $p < 0.001$) and time to mean grip aperture (F (1, 14) = 19.24, $p < 0.001$), with the mean grip aperture being narrower and occurring later as scene complexity increased. Mauchly's test found no violations of the assumptions of sphericity for the grasp component. The results of planned contrasts indicated that there was a significant difference for both mean grip aperture and time to mean grip aperture between blocks 1 and 2 (t (1, 14) = 6.4, $p < 0.0001$, t (1, 14) = -4.60, $p < 0.001$), and between blocks 1 and 3 (t (1, 14) = 7.59, $p < 0.0001$, t (1, 14) = -5.91, $p < 0.0001$), respectively.

Table 4.
Summary of the main effect of viewing condition, scene complexity, and the interaction term for each dependent measure relating to the grasp component**.**

Dependent measure	Main effect of viewing condition			Main effect of scene complexity		Viewing condition x scene complexity interaction	
Mean grip aperture (mm)	F (1,7) = 1.98	$p < 0.20$	n/s	F (1,14) = 33.13	$p < 0.001$	F (1,14) = 0.16	$p = 0.86$
Time to mean grip aperture (ms)	F (1,7) = 0.46	$p = 0.52$	n/s	F (1,14) = 19.24	$p < 0.001$	F (1,14) = 2.41	$p = 0.13$

3.1.2. Obstacle avoidance

There was a significant main effect of scene complexity upon the amount of obstacles knocked over (F (1, 14) = 10.33, $p < 0.01$), but there was no significant effect for viewing condition. See also figure 3. No significant interactions between viewing condition and scene complexity for the grasp component were found. Planned contrasts for the amount of obstacles knocked over and scene complexity found a significant difference between scene 1 and 3 (t (1, 14) = -4.43, $p < 0.001$) and scene 2 and 3 (t (1, 14) = -3.09, $p < 0.01$).

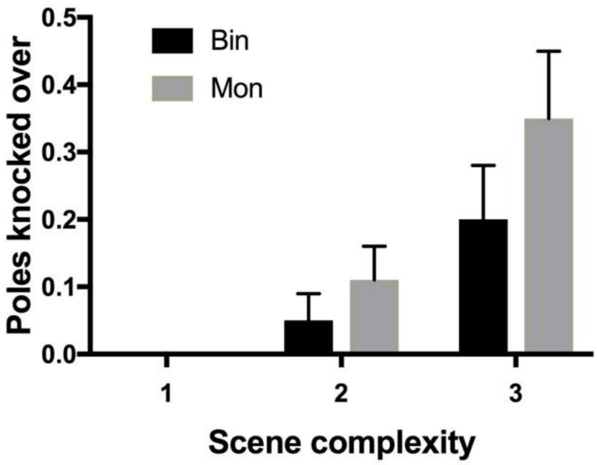

Figure 3. Obstacles knocked over in experiment 1

A graph showing the average amount of poles (obstacles) knocked over under binocular/monocular viewing relative to scene complexity. N.B. Scene 1 does not show any poles knocked over due to the isolated nature of that scene (without obstacles).

3.2. Experiment 2

Once again individual means and the average standard error of the mean for each dependent measure were calculated for each viewing condition. For experiment 2, overall performance of the kinematic measures relative to viewing condition with the inclusion of motion parallax were compared with performance from scene 3, experiment 1 (without motion parallax). Table 5 shows the mean and standard error of the mean for each measure.

A two way repeated measures ANOVA was carried out using R. The first factor was viewing condition (with two levels, binocular and monocular), and the second factor was the presence of motion parallax (with two factors, present or absent). These analyses were carried out for each dependent measure, as per experiment 1.

Table 5.
Comparison of the kinematic measures relative to binocular/monocular viewing without motion parallax, derived from experiment 1, and binocular/monocular viewing with motion parallax found in experiment 2. Table 5 illustrates mean values and SEM in parentheses.

Dependent measure	**Viewing condition (motion parallax absent – experiment 1)**		**Viewing condition (motion present – experiment 2)**	
	Binocular	Monocular	Binocular	Monocular
Movement latency (ms)	269.3(30.7)	245 (13.2)	289.3 (22.1)	289.9 (16)
Movement duration (ms)	705.6 (26.7)	740.2 (34.3)	659.6 (20.4)	717.7 (24.5)
Peak acceleration (cm/s-2)	465 (47.5)	731.3 (198.8)	572.3 (69.5)	556 (84.4)
Peak velocity (mm/s)	121.4 (5.7)	126.2 (7.2)	127.8 (7.7)	123.1 (6.2)
Velocity at end (ms)	8.4 (2.7)	13.5 (3.5)	19.5 (7)	10.5 (2.2)
Time to peak acceleration (ms)	102 (8.3)	89.4 (11.6)	123.6 (22)	134.7 (53.4)
Time to peak velocity from start (ms)	204.2 (12)	206.3 (13.9)	187.3 (13.7)	189.4 (11.1)
Time to peak velocity to end (ms)	501.4 (22.7)	533.8 (24.7)	471.7 (12.3)	528.5 (23.1)
Mean grip aperture (mm)	8.9 (0.1)	9 (0.1)	8.5 (0.1)	8.8 (0.2)
Time to mean grip aperture (ms)	555.7 (31.6)	532.9 (32.5)	478.6 (37.2)	526.8 (26.5)
Poles knocked	0.19 (0.08)	0.35 (0.08)	0.15 (0.05)	0.23 (0.05)

3.2.1. Transport component

Table 6 shows a summary of the main effects and interaction analyses for each dependent measure for the transport component. There was a significant main effect of viewing condition for time to peak velocity to end (F (1, 7) = 7.82, p < 0.05), but no other significant main effects. However, in experiment 2, the effect of viewing condition upon movement duration (F (1, 7) = 5.05, p = 0.06) was approaching significance. Motion parallax acted as main effect on movement latency (F (1, 7) = 7.80, p < 0.05), reaching significance. Planned contrasts for movement latency illustrated a significant difference between monocular viewing (without motion parallax) and monocular viewing (with motion parallax) (t (1,7) = -3.26 , P < 0.01), with the direction of the effect toward the opposite direction of what was expected. Planned contrasts for time to peak velocity to end found a significant difference between binocular viewing (with motion parallax) and monocular viewing (with motion parallax) (t (1,7) = -2.50 , $p < 0.05$), with binocular vision (with motion parallax) reducing time to peak velocity to end significantly in contrast to monocular viewing (with motion parallax). No significant interactions between viewing condition and motion parallax for the transport component were found.

Table 6.
Summary of the main effect of viewing condition and motion parallax for each kinematic measure relating to the transport component.

Dependent measure	**Main effect of viewing condition**			**Main effect of motion parallax**			**Viewing condition x motion parallax**		
Peak acceleration (cm/s-2)	F (1,7) = 0.67	p = 0.44	n/s	F (1,7) = 0.18	p = 0.69	n/s	F (1,7) = 2.66	p = 0.15	n/s
Peak velocity (mm/s)	F (1,7) = 0.001	p = 0.98	n/s	F (1,7) = 0.15	p = 0.71	n/s	F (1,7) = 1.30	p = 0.29	n/s
Time to peak acceleration (ms)	F (1,7) = 0.002	p = 0.96	n/s	F (1,7) = 0.71	p = 0.58	n/s	F (1,7) = 0.27	p = 0.62	n/s
Time to peak velocity from start (ms)	F (1,7) = 0.11	p = 0.75	n/s	F (1,7) = 1.37	p = 0.28	n/s	F (1,7) = 0.002	p = 0.97	n/s
Time to peak velocity to end (ms)	F (1,7) = 7.82	p < 0.05		F (1,7) = 1.86	p = 0.22	n/s	F (1,7) = 0.57	p = 0.48	n/s

3.2.2. Grasp component

Once again, mean grip aperture and time to mean grip aperture were unaffected by viewing condition. Although the grasp component was also unaffected by motion parallax, mean grip aperture (F (1, 7) = 4.97, $p < 0.06$) was approaching significance. Planned contrasts uncovered no significant difference for the grasp component for either viewing condition or motion parallax. No significant interactions between viewing condition and motion parallax for the grasp component were found.

Table 7.
Summary of the main effect of viewing condition and motion parallax for each kinematic measure relating to the grasp component.

Dependent measure	**Main effect of viewing condition**			**Main effect of motion parallax**			**Viewing condition x motion parallax**		
Mean grip aperture (mm)	F (1,7) = 2.44	p = 0.16	n/s	F (1,7) = 4.97	P = 0.06		F (1,7) = 2.21	p = 0.19	n/s
Time to mean grip aperture (ms)	F (1,7) = 0.96	p = 0.36	n/s	F (1,7) = 2.41	p = 0.16	n/s	F (1,7) = 2.23	p = 0.18	n/s

3.2.3. Obstacle avoidance

There was no significant main effect of viewing condition upon obstacles knocked over for experiment 2 (F (1, 7) = 5.21, p = 0.06). However, the amount of obstacles knocked over was less under binocular viewing (M = 0.17, SEM = 0.04) than under monocular viewing (M = 0.29, SEM = 0.05), approaching significance. Moreover, fewer obstacles were knocked over under monocular viewing with motion parallax (M = 0.35, SEM = 0.083) than under monocular viewing without motion parallax (M = 0.23, SEM = 0.052). See figure 2. No significant interactions between viewing condition and motion parallax for the grasp component were found.

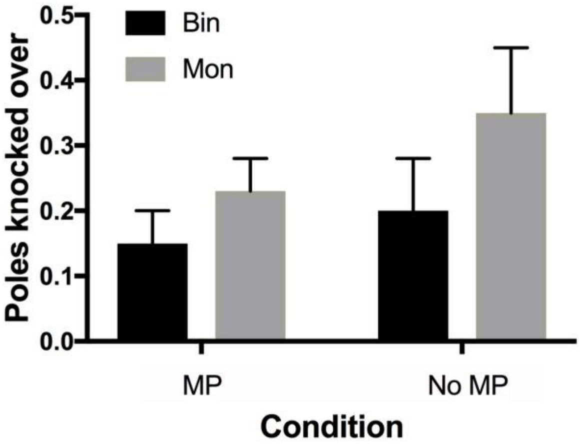

Figure 4. Obstacles knocked over in experiment 2

A graph showing the difference of the average amount of poles (obstacles) knocked over relative to motion parallax (MP) or no motion parallax (no MP) under binocular/monocular viewing.

Chapter 4: Discussion

The current study aimed to uncover the role of binocular vision in natural prehension movements when in the presence of obstacles. Moreover, the study wanted to obtain further information about which component of the reach and grasp movement was influenced advantageously by the use of two eyes, as opposed to one. Participants interacted within a naturalistic environment, with real-world objects embedded in each visual scene. Familiar visual cues used in everyday scenes were available for participants to guide in the prehensile task. That is, pictorial cues (i.e. height in the visual field, retinal image size, familiar object size, interposition, etc.)

were always available, which are necessary when binocular information is inaccessible. To determine the advantages of binocular vision, the goal-directed movement was divided into the transport and grasp component, so that assessing the kinematic measures, and hence prehensile performance relative to viewing condition, provided clarity of binocular vision's role. The current study intended to confirm previous findings of prehension in relation to viewing condition and motion parallax, and to pursue an examination of obstacle avoidance behaviours during added scene complexity. The latter consideration of obstacle avoidance had been examined in previous studies; however, the use of varying scene complexity during prehension and the difficulty involved in the study's sensorimotor task was a novel undertaking.

4.1. The effect of viewing condition on prehension

As has been discussed, several studies have found a division in the usefulness of binocular information during prehension (Watt and Bradshaw, 2000; Watt and Bradshaw, 2002; Greenwald, Knill, Saunders, 2005; Melmoth and Grant, 2006). This division referred to the transport and grasp component of the prehensile movement, with binocular vision appearing to be more important during the end phase of the transport component, and particularly important during the terminal phase of the grasp component. In both experiments of the current study, the removal of binocular information during monocular viewing did not affect the primary kinematic measures during the early phase of the reach of the transport component. The movement latency and velocity profiles were similar during the initial reach, with statistical analyses confirming the equivalence between binocular and monocular conditions. Such a result suggests that monocular vision contains sufficient depth information to skilfully program and control prehensile movements, especially during the early phase of the reach as found by Marotta and Goodale (1998, 2001). This may come from the fact that programming and controlling the reach does not necessarily require accurate distance information, because its function is to position the hand in close proximity of the target object, but not actually upon the object.

It was hypothesized that movement duration should be reduced significantly under binocular viewing in contrast to monocular viewing. However, both experiments of the current study found no significant difference between movement duration times and viewing condition. Nevertheless, it was found that movement duration on average was extended under monocular viewing. This was thought to be the case due to an extended end phase (deceleration time) of the prehensile movement. This extended deceleration time appears to occur because monocular vision degrades important spatial information, which can only be acquired through the disparity of images of the two eyes (stereopsis). Because of this, when the hand is in close proximity of the target object, it slows down in an attempt to combat the visual uncertainty that ensues from the use of one eye. In the present study, it was found that the time to peak velocity to end (deceleration time at the end of the reach) was significantly drawn-out under monocular viewing during both experiment 1 and 2, perhaps extending the overall movement duration, though not significantly. This phenomenon was found in several studies (Melmoth and Grant 2006, Saling, et al., 1998; Watt and Bradshaw, 2000; Watt and Bradshaw, 2002), wherein deceleration times of the end phase of the reach were lengthened significantly under monocular viewing due to positional uncertainty. As a result, in these studies movement duration was extended significantly under monocular viewing. With this in mind, the end phase of the reach appears to be the point at which binocular vision begins to afford advantages in prehension, carrying over to the grasp component.

Unlike several studies (Servos, et al., 1992; Jackson, et al., 1997; Watt and Bradshaw 2000, 2002), no differences in the grasp component (mean grip aperture, time to mean grip aperture) were found during experiment 1 and 2 of the current study with regards to viewing condition. It was hypothesized that due to several obstacle-infused scenes that would have to be navigated, participants using monocular vision would produce narrower grip apertures to accommodate positional uncertainty and reduced space in the cluttered scene, in comparison to grip apertures under binocular viewing. However, it was also cautioned that the inverse may be true, as found by Watt and Bradshaw, 2000, so that wider grip apertures are assumed under monocular viewing, due to reduced depth information, especially in scene 1 (impoverished scene). Neither consideration was found in relation to viewing condition; that is, grip apertures were not significantly affected by viewing condition regardless of the scene. An interesting finding was that additional visual information arising from a cluttered environment did not improve prehensile performance under binocular viewing in contrast to monocular viewing. What is meant by improving prehensile performance is the lessening of the movement duration, an increase in the peak velocity profiles, and a decrease in the time to peak velocity and acceleration profiles. The fact that this did not occur in the current study opposes the results of Jackson, et al. (1997), who reported that when there was an additional non-target object present, reaching and grasping performance was more dependent upon binocular vision. Also in opposition to this reported claim, Watt and Bradshaw (2002) found no significant interaction between binocular and monocular viewing and the number of non-target objects presented in the scene. This previous finding, coupled with the current study's result, suggests that binocular information used in the control of prehension within a cluttered scene including multiple non-target objects may not be essential.

It was interesting to note that even in the impoverished scene where target objects were in isolation, the kinematic measures (both transport and grasp components) were largely unaffected by viewing condition. This is reminiscent of Jackson et al. (1997) who found no advantages in the use of binocular vision for reaching and grasping movements to isolated objects. However, perhaps this could be explained because their participants were issued an extended scene preview (approximately 15 s) to perceive the scene before reaching and grasping. Furthermore, their participants were always interacting with the same target object positioned at 25 cm off midline locations (Jackson, et al. 1997). Within their study, the combination of an extended preview period and object familiarity due to a lack of variation of object distances, could have allowed for improved monocular performance. In the present study, although participants reached and grasped for one of three target objects in a randomized fashion, only differing laterally, they were always at distance of 30 cm from the observer. Perhaps the lack of variation in target distance allowed the participants to learn the target locations much quicker than they would have if the target distances were varied. Thus, this could have concealed the effects of viewing condition upon prehension. Be that as it may, such issues apply to everyday scenes as well as laboratory settings, with evidence mounting that visuomotor planning may benefit a lot more from previous experience and practice than does online control movements (Jackson, et al., 1997; Glover, 2002, 2003; Rossetti, et al. 2003). This is because planning relies more upon perceptual memories, associated with the ventral stream, as discussed earlier.

4.2. The effect of scene complexity on prehension

As noted earlier, McKee and Taylor (2010) looked at depth judgements for objects presented in a visual scene relative to viewing condition. They used an austere setting and later an enriched setting to determine the precision of viewing thresholds, finding that a more complex scene increased monocular thresholds, due to an increase in depth cues in the scene. Although McKee and Taylor (2010) focused upon perceptual judgements only, the current study used the idea of different visual settings, focusing instead upon prehension and obstacle avoidance in relation to scene complexity and viewing condition. It was queried whether a more enriched setting (cluttered scene) would provide important information to be used in reaching and grasping movements. Perhaps this information could be used to allow monocular viewing to compare with the performance under binocular viewing in the prehensile task. However, as has been discussed above, viewing condition did not affect prehensile performance on the vast majority of kinematic measures in all scenes of experiment 1, and in the cluttered scene of experiment 2. That is, only slight glimpses were observed that binocular vision is important during prehension. Although viewing condition did not substantially affect reaching and grasping performance, the current study found that scene complexity did. In experiment 1, with the inclusion of several obstacles in scene 2 and 3, participant’s performance during the transport component showed significantly extended movement duration times, reduced peak velocity profiles, and extended time to peak velocity profiles. Thus, the presence of obstacles created a more difficult prehensile task, as participants’ trajectories toward the target objects had to be altered considerably to avoid collisions with those obstacles.

Mon-Williams, et al., (2001) found that during prehension the presence of obstacles caused the hand of participants to slow down considerably and movement times to increase. In their experiment, the obstacles were presented in a way so as to not obstruct the hand's path toward the target object. What was touched upon earlier is related to this last design feature. That is, even obstacles that are not placed in locations that obstruct the spatial path toward a target are still avoided in an exaggerated fashion. This probes the conservativeness of the visuomotor system in performing obstacle avoidance behaviours. Mon-William, et al. (2001) also found differences in the velocity profiles, movement times, and grip apertures depending upon where the obstacles were located; however, this is beyond the scope of the current study. Unlike the study by Mon-Williams, et al. (2001) and other similar studies on obstacle avoidance, the current study placed obstacles that would sometimes impede the hand's path toward the target objects, but not necessarily obstructing the participant's view of those targets. This was done to provide a richer visual scene, increase disparity gradients, provide a more difficult task to further examine the sensorimotor capabilities of the visuomotor system, and because in everyday settings obstacles may be located anywhere around a target object, in a lot of cases obstructing the hands path.

In experiment 1 of the present study, it was found that movement duration times were significantly extended as a result of increased scene complexity. This makes sense as the more obstacles there are to avoid, the more time it would take to perform online control and select a trajectory to avoid colliding with those obstacles. Furthermore, peak velocity was found to be reduced with added scene complexity. Once again, this seems reasonable because if there are obstacles present there would be reduced space for the hand to achieve a greater velocity. Additionally, it is no surprise that time to peak velocity to end profiles were reduced as a function of added scene complexity. This is because obstacles are in the way of the target objects and the visuomotor system must accommodate the obstacles' position when performing online control, hence increasing deceleration time. An interesting finding was the increase in time to peak velocity from start profiles with added scene complexity. It seems that within a more complex scene (scene 2 or 3), the hand of participants would achieve a peak velocity earlier in the reach, and then begin to slow down much earlier than if no obstacles were present (i.e. scene 1).

With regard to experiment 1 of the present study, the grasp component of the prehensile task was affected considerably by scene complexity, as hypothesized. It was found that with increased scene complexity mean grip apertures were reduced to accommodate the obstacle placements, regardless of viewing condition. Reducing the grip aperture is an effective way to prevent colliding with the obstacles. Furthermore, the time to action the mean grip aperture was also significantly affected by scene complexity, with a much longer time taken under scene 2 and 3 in contrast to scene 1. Again, due to the obstacles that obstructed the path toward the target objects, deceleration times were increased and as a consequence, mean grip aperture times were increased. These events transpired due to the prudent behaviour of participants in attempting to avoid collisions with the obstacles.

4.3. The effect of motion parallax on prehension

During experiment 1, the heads of participants were positioned upon a chin rest to prevent unwanted head motion. However, the chin rest was removed for experiment 2 when motion parallax was made available to participants by allowing lateral head movements. The second experiment was interested in determining whether motion parallax would improve prehensile performance and obstacle avoidance in a cluttered scene. As noted, motion parallax is a powerful monocular cue that can provide useful depth information in the absence of stereopsis. It was discussed that those with binocular deficiencies (i.e. from amblyopia) use motion parallax to accommodate their condition, yet it remains unclear to what extent the depth information ascertained by an observer from motion parallax can be used in the control of prehensile movements and obstacle avoidance. It was hypothesized that during experiment 2, motion parallax would increase prehensile performance under monocular viewing over monocular viewing without motion parallax (from experiment 1). However, although it was found that movement duration times were reduced under monocular viewing with motion parallax in comparison to without motion parallax, the result was not significant. Interestingly, movement duration was reduced more under binocular viewing with motion parallax in comparison to without motion parallax, than under monocular viewing. It was difficult to determine why this was the case as motion parallax has not been found to improve binocular vision.

Movement latency for both viewing conditions was significantly affected by motion parallax; however, the effect was in the opposite direction to what was expected. That is, movement latency under both binocular and monocular viewing was extended during experiment 2 with the inclusion of motion parallax, as opposed to experiment 1 without. It was discussed that motion parallax may not provide additional depth information when binocular cues are accessible (Marotta, Kruyer, and Goodale, 1998; Watt and Bradshaw, 2003). However, when binocular information is not available, depth judgements and prehensile performance under monocular viewing may improve from the use of motion parallax (Marotta, et al., 1998). Furthermore, it was noted that motion parallax may only help monocular viewing during the early phase of the reach of a goal-directed movement. However, experiment 2 of the current study did not find these considerations to be the case, with both viewing conditions suffering from the use of motion parallax in movement latency (initiation of the movement). Perhaps it was the participants' lack of exposure and familiarity with generating head motion to accommodate reduced depth information before reaching, and the difficulty of the sensorimotor task, that produced this result.

It was thought perhaps that performance under monocular viewing during experiment 2 may increase due to the provided depth information from motion parallax, and even be comparable to binocular vision. However, McKee and Taylor (2016) found that depth judgements were always superior under binocular viewing in contrast to monocular viewing, even if such judgements were improved under monocular viewing with the use of motion parallax. As stated, monocular vision itself remains relatively useful in the control of prehension as found by Marotta and Goodale (1998, 2001), perhaps even increasing in usefulness with extended practice and exposure (Marotta, Perrot, Nicolle, and Goodale, 1995). Moreover, the use of motion parallax may still be important for depth judgements to be used in prehensile movements when binocular information is unavailable. However, the use of motion parallax in a cluttered scene, where the task demands are difficult due to the complexity of the scene, may make it less useful than for simple prehensile tasks and for strictly perpetual judgement tasks. Further studies must be carried out to determine the use of motion parallax in obstacle avoidance in cluttered scenes.

4.4. Obstacle avoidance in cluttered scenes

As has been discussed, humans are highly proficient at avoiding collisions with non-target objects (obstacles) while executing goal-directed movements. People have anti-collision strategies that permit online control, which modifies the hand movement during the reach in a subtle and adaptive fashion (Mon-Williams, et al., 2001; Sabes and Jordan, 1997; Tresilian, 1998). Within the presence of obstacles, the visuomotor system finely adjusts the spatial and temporal features of the hand movement allowing for successful obstacle avoidance. For example, to accommodate clutter, the visuomotor system slows down the movement so the probability of the fingers colliding with the obstacles is reduced (Mon-Williams, et al., 2001). Another strategy is to reduce the grip aperture between the thumb and forefinger when pre-shaping the hand to grasp an object in the presence of obstacles. In terms of viewing condition, it was hypothesized that due to the uncertainty of depth judgements that occur under monocular viewing, participants should knock over more obstacles. The current study found that although more obstacles were knocked over under monocular viewing, the statistical analyses did not produce a significant result. That is to say, viewing condition did not significantly affect the amount of obstacles knocked over during experiment 1 or 2. However, it appears that viewing condition may be influential upon the amount of obstacles knocked over, but due to the large standard errors of the mean involved in the data in relation to this measure, especially in experiment 1, a definite statement cannot be made on the matter. Further studies must be conducted to gain clarity in this feature of obstacle avoidance relative to viewing condition. As was expected and hypothesized, added scene complexity amounted to more obstacles being knocked over. It is clear that the more cluttered the scene is, and the more obstacles present, the greater the likelihood that an individual will knock over an obstacle, regardless of viewing condition.

As noted, depth information acquired from a cluttered scene with multiple objects has been found to be important in depth judgements (Diedrichsen, et al., 2004; Obhi and Goodale, 2005, McKee and Taylor, 2010). However, other studies have found that additional objects in a scene may not affect prehensile control (Watt and Bradshaw, 2000; 2002). Furthermore, in a cluttered scene where the spatial path toward target objects is difficult to navigate, this additional visual information may not be of help due to the difficulty in the task. The initial idea was that binocular disparity would provide more depth information within a complex scene because of a larger amount of spatial points being compared, and multiple objects acting as frames of reference, providing more visual information to the observer. In this way, the observer acquires more depth information to aid in the prehensile movement, and can therefore be more proficient in accomplishing the task. Yet, the current study found no difference in performance between binocular and monocular viewing when additional objects were present in the scene, which were thought to improve depth judgements under binocular viewing due to increased disparity gradients at the visuomotor system's disposal. However, perhaps due to the fact that information derived from pictorial cues (monocular information) are also improved in an enriched visual scene, and are used when viewing monocularly, performance under monocular vision is comparable to that of binocular vision. Further studies must be conducted to disentangle these ideas relating to additional visual information provided in complex scenes and its use in prehension and obstacle avoidance.

Within real world settings, there are situations where binocular information is imperative, such as when objects are presented at eye height or when flankers or obstacles partially occlude target objects (Morgan, 1989). However, the current study did not observe dependence upon binocular cues during prehension and obstacle avoidance within cluttered scenes. Such findings confirm the results of others (Ma-Wyatt, McKee, Verghese, 2004; Watt and Bradshaw, 2000, 2001) to the extent that the guiding of accurate hand movements and prehensile movements may not be as dependent upon binocular information as was thought previously.

4.5 Limitations

The current study's design was such that participants interacted with repetition the same limited number of objects and visual environments. Although the target objects varied laterally, they were at a fixed distance from the participant. It could be that similarity in viewing condition performance with regards to prehension and obstacle avoidance occurred due to a lack of variation of target object distance, allowing the participants to learn the layouts and reach trajectories quicker than if the distances were varied. This problem arose in Jackson et al. (1997), where a lack of variation of target locations, combined with an extended scene preview before each trial, could have explained the absence in reaching and grasping performance to isolated target objects under binocular and monocular viewing. In the current study, the impoverished scene produced minimal differences between binocular and monocular viewing on most kinematic measures. Furthermore, during added scene complexity it was also observed the absence of differences between viewing conditions. However, perhaps this lack of difference was due to the task demands and the difficulty with performing the task. A study with more varied object distances and locations in relation to scene complexity and obstacle avoidance will provide clarity toward these points. Additionally participants were free to observe the scene before the beginning of a trial, with no constraints upon fixation locations. Restricting participants' point of fixation was considered, however, it was opted that because in everyday scenes we are unlikely to constrain our point of fixation, giving attention to portions of the scene of interest in a less rigid fashion, such an imposition was not included. That being said, participants only had a brief (few seconds) to view the scene before the start of each trial.

Although it has been found that the presence of flankers may increase prehensile performance, due to greater visual information being provided, in terms of the current study, this was difficult to determine because the obstacles were placed in the path of the hand toward the target objects. So, even if greater depth information is existent in the more complex scenes, it may not be able to be used effectively by the observer because of the difficult-to-navigate layouts. This was observed in both experiment 1 and 2 of the current study. When the task is more difficult, perhaps it is the case that such additional information cannot be used in the online control of the reach and in the terminal phase of the grasp, because of reduced space and increased task demands. Further studies using difficult layouts with regards to prehension and viewing condition must be conducted to clear up this potential confound.

During experiment 2, motion parallax did affect prehensile movements and obstacle avoidance as much as expected. Perhaps the use and execution of motion parallax icould have been managed and monitored more efficaciously. That is, it could be that the participants required more practice trials before the official trials, to gain comfort in the use of self-generated head motion before reaching and grasping. It was noticed that some participants found it difficult to coordinate the sequence of motion parallax, pressing the star button, halting the head motion and then executing the reach and grasp movement. Due to the unfamiliarity of using this monocular cue, because all participants possessed normal vision and were not used to such a strategy, this could have influenced the results.

4.6 Future directions

Future studies will need to be conducted to further understand the use of obstacle avoidance during prehension in cluttered scenes. Moreover, viewing condition relative to cluttered scenes also needs to be further assessed, to establish whether binocular information is all that important during obstacle avoidance. Also in need of clarification is the use of additional depth information in a scene due to an enriched setting, and how this information can be used to program prehensile movements that avoid collisions with obstacles. Furthermore, the importance of motion parallax during prehension and obstacle avoidance in cluttered scenes, especially when binocular information is unavailable, must also be examined further. Another important direction is the effects of monocular learning over extended exposure, and thus how monocular performance can be increased over time in relation to goal-directed actions.

A next step could allow for the accomplishment of everyday tasks, especially focusing upon reaching and grasping and the accompanied eye movements. This will give a clearer indication of how the visuomotor system executes more complex tasks, and how visual fixations accompany the motor actions in tandem. Research into more complex and longer duration tasks that we accomplish everyday will provide more insight into the visuomotor system and its obstacle avoidance capabilities. As a beginning inquiry, two studies have investigated the relationship between eye and hand movements in everyday food and beverage preparation tasks. Firstly, a study by Land, Mennie, and Rusted, (1999) looked at tea making, in which 40 - 50 separate actions were performed to accomplish the task. Furthermore, a study by Hayhoe (2000) focused upon a sandwich making task, as participants sat down at a table. The next step would be for participants to perform these types of everyday activities in cluttered environments and compare the performance under binocular/monocular viewing, even with varying amounts of clutter. By studying such complex everyday tasks, in naturalistic environments, the *modus operandi* of the visuomotor system and the influence of viewing condition may be uncovered.

Another direction perhaps is to look at visual field loss in relation to viewing condition, and how such a deficit may affect obstacle avoidance behaviours during more complex activities, such as sandwich making, for instance. This will provide a greater understanding of the visuomotor system and what deficits in action may ensue, not to mention how the visuomotor system accommodates for such a reduction in visual information (due to a lack of binocular disparity from visual field loss) as such information is used to perform goal-directed actions.

4.7 Conclusion

The current study examined the use of binocular vision in sensorimotor control to determine whether it was necessary when performing prehension and obstacle avoidance. The current study also aimed to gain insight into the obstacle avoidance capabilities of the visuomotor system in cluttered scenes. The results of the present study found that added scene complexity (more obstacles) significantly affected prehensile performance, but viewing condition did not appear to do the same. Therefore, binocular vision may not be fundamental in such tasks, especially when the task demands are high. However, it is still difficult to explain the lack of variance between binocular/monocular viewing on prehensile movements. This is because there was not only a lack of variance in the cluttered scene, which could be explicated by the difficulty of navigating the workspace layout regardless of viewing condition, but even in the impoverished scene (scene 1) there was very little difference in performance. Regardless, it appears that monocular vision is quite useful in programming and controlling reaching and grasping movements. That being said, more obstacles were knocked over during monocular viewing than under binocular viewing. Further studies must be conducted to elaborate upon these findings and to gain clarity in the use of additional depth information in cluttered scenes to execute goal directed-actions.

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Appendix A – Participant information sheet

Participant information sheet

Project title: The role of binocular vision in sensorimotor control

Principal investigator:
Supervising researcher: A/Prof Anna Ma-Wyatt

Welcome,

You have been invited to participate in the research project which is in relation to my Honours thesis. The research will be conducted at the University of Adelaide by myself, under the supervision of Associate Professor Anna Ma-Wyatt.

What is the project about?

In everyday table-top settings our visuomotor system allows us to successfully reach for and grasp objects, all the while avoiding obstacles that impede our path. We are investigating how binocular and monocular views of a scene contribute to performance of naturalistic reaching.

Why am I being invited to participate?

We are seeking healthy adults to participate in the experiment at the University of Adelaide. Participants should have normal or corrected to normal vision and have no history of eye complications or motor deficits.

What will I be asked to do?

Participants will be required to complete a Randot stereotest to determine whether they have stereo vision before they commence the experiment. The main task will involve participants being presented with target objects that they will be asked to reach and grasp. In subsequent workspace layouts, they will further be required to avoid collisions with obstacles that will surround the target objects. Hand movement trajectories will be recorded during each trial. For those that inquire, the experimenter wil;l be happy yo provide information during the experiment. Additionally, a comprehensive rundown of the results may be given after completion.

Are there any risks involved with participating in the study?

There is a slight chance of muscle fatigue from repeated arm reaching. Breaks will be provided between each block of fifteen trials. Participants may withdraw from the study at any time without penalty.

What are the benefits of this research?

This study advances theories of sensorimotor control, especially how visual information contributes to reaching and obstacle avoidance.

[redacted]

What will happen to my information?

The collected data will be treated confidentially and will be secured on password-protected computers that will only be accessed by the experimenters. If the data acquired from the experiment is used in publications, then measures will be taken to de-identify individual participants.

What if I have a complaint or concerns?

The study has been approved by the Human Research Ethics Committee at the University of Adelaide. If you have any questions associated with the experimental procedure or your participation, you should contact the principal investigator. If you have any concerns or complaints, please contact the project co-ordinator A/Prof Anna Ma-Wyatt on 8313 5660, email anna.mawyatt@adelaide.edu.au, or the head of the Human Research Subcommittee in the School of Psychology, Dr. Paul Delfabbro on 8313 4936, email paul.delfabbro.edu.au.

Who do I contact for more information or If I want to participate?

Please contact myself for further information.

Your sincerely,

School of Psychology

University of Adelaide

[redacted]

Appendix B – Edinburgh Handedness Inventory

Edinburgh Handedness Inventory

INSTRUCTIONS: Indicate your preference in the use of the hands for the following activities:

	Left	*Right*	*Either*
1. Writing			
2. Drawing			
3. Throwing			
4. Scissors			
5. Toothbrush			
6. Knife (without fork)			
7. Spoon			
8. Broom (upper hand)			
9. Striking match (match)			
10. Opening box/lid			

Source: Oldfield, R. C., "The Assessment and Analysis of Handedness: The Edinburgh Inventory." *Neuropsychologia* 9 (1971):97–113.