The Role of Binocular Vision during the Performance of Complex Manipulation Skills

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

The overall goal for this thesis was to examine the significance of binocular vision during the performance of complex manipulation tasks in visually-normal children and adults. The goal of study 1 was to examine the age-related contribution of binocular vision to the performance of manipulation skills. Healthy children (n=58, age: 5-13 years) and adults (n=19, age:17-38 years) performed two manipulation tasks: peg-board and bead-threading, under randomized viewing conditions (binocular, right and left-eye monocular). The main outcome measure was movement time to complete the task. Results showed that the contribution of binocular vision differs based on age (i.e., greater in children) and on the task (i.e., greater in the bead-threading task).

In study 2, the goal was to examine the significance of binocular vision during the performance of complex manipulation tasks in children with learning difficulties. Thus, the performance of fine motor skills was compared among children with learning difficulties (n=19, age: 5-12 years) and their age-matched peers tested in study 1. Results showed that children with learning difficulties were significantly slower than their peers on the bead-threading task, but performed similarly to their peers on the peg-board task.

The aim of study 3 was to characterize the role of binocular vision in the performance of manipulation tasks involving tool use in visually-normal adults. Healthy adults (n=36, age: 17-38 years) performed five manipulation tasks (bead-threading, peg-board with fingers, and with tweezers, precision pointing with a tool, and picking up a target using a hook-tool) during binocular and monocular viewing. Results showed that binocular vision provides critical sensory input when the task involves precise manipulation of small objects, either when using hands directly or when using a tool to pick up the object.

This thesis has two main conclusions. First, the importance of binocular vision for the performance of manipulation skills is highly dependent on the task. An important implication of this work is that a binocular visual screening is recommended for persons whose occupation requires manipulation of small object. Second, the ability to perform skilful manipulations improves significantly during development and our results indicate that normal binocular vision plays an important role in this process. Furthermore, the performance of fine motor skills differentiates between children with and without learning difficulties. Based on these results, including an assessment of fine motor skills in children with abnormal binocular vision and children with learning difficulties is highly recommended.

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Chapter 1: Introduction

1.1 Background information

Across the human life span, vision provides an important sensory input for most of our daily activities, including social communication, reading, writing, as well as skillful motor tasks performed with our hands. While the contribution of vision to the development of cognitive functions has been studied extensively (Kulp & Schmidt, 1996; Goldstand, Koslowe, & Parush, 2005; Buzzelli, 1991; Quaid & Simpson, 2013), the role of vision, and in particular, binocular vision in the development of fine motor skills has not received similar attention (Grant, Suttle, Melmoth, Conway, & Sloper, 2014; Suttle, Melmoth, Finlay, Sloper, and Grant, 2011; Watt, Bradshaw, Clarke, & Elliot, 2003). Binocular vision, an aspect of vision, which entails processing of inputs from both eyes in order to determine the object's location in the three-dimensional space, is important for the performance of fine motor skills. However, binocular vision is disrupted in some visual disorders such as amblyopia (lazy eye), or strabismus (misaligned eyes).

An extensive body of evidence shows that visuomotor coordination and binocular vision continue to improve in normally developing children between birth and early teenage years. To our knowledge, only three studies in the literature have examined the significance of binocular vision in planning and executing of simple reach-to-grasp movements in visually-normal children (Grant et al., 2014; Suttle et al., 2011; Watt et al., 2003). These studies showed age-related differences in the role of binocular vision in movement planning and execution. Specifically, younger children were dependent on binocular vision during movement planning, but not during execution. In contrast, older children relied on binocular vision during movement execution. Aside from the relatively simple task of reaching and grasping, the functional significance of binocular vision during performance of complex manipulation skills in visually-normal children is currently unknown. This cross-sectional study will provide knowledge about the developmental trajectory linking binocular vision and performance of fine motor skills in visually-normal children.

It is important to understand the role of binocular vision in the development of fine motor skills in visually-normal children because disturbance of binocular vision is one of the most common childhood vision disorders. For example, 2 to 3% of children have abnormal binocular vision due to amblyopia where 50% of cases with unilateral amblyopia are associated with strabismus (American Academy of Ophthalmology [AAO], 2013 ; Drover, Kean, Courage, & Adams, 2008). Furthermore, children with developmental delays, such as cerebral palsy (Ghasia, Brunstrom, Gordon, & Tychsen, 2008), autism (Simmons, Robertson, McKay, Toal, McAleer, & Pollick, 2009), or Down's Syndrome (Tsiaras, Pueschel, Keller, Curran, & Giesswein, 1999) have a greater prevalence of disorders of binocular vision, including amblyopia and strabismus. There is mounting evidence which shows that children with abnormal binocular vision are more likely to have difficulties with reading and fine motor skills (Birch, 2013; Buzzelli, 1991; Goldstand, Koslowe, & Parush, 2005; Grant, Melmoth, Morgan, & Finlay, 2007; Grant et al., 2014; Kulp & Schmidt, 1996; O'Connor, Birch, Anderson, Draper, & the FSOS Research Group, 2003; Quaid & Simpson, 2013, Suttle et al., 2011; Webber, Wood, Gole, & Brown, 2008). This evidence indicates that binocular vision might have an important role in the development and learning of fine motor skills. Understanding the role of binocular vision in the development of fine manipulation skills is critically important for developing effective rehabilitation programs for children with abnormal binocular vision due to amblyopia and/or strabismus. In particular, the outcome of this study will provide normative data that can be used as a benchmark for evaluating the visuomotor performance of children with abnormal binocular vision.

Binocular advantage is defined as the extent to which binocular viewing results in improved performance in comparison to monocular viewing (Howard, 2012). The effect of task difficulty on motor performance has not been examined during development, and our current knowledge on this topic in adults is limited. However, several studies have shown that the importance of binocular vision for task performance varies depending on the complexity of the manipulation task (Piano & O'Connor, 2013; Read, Begum, McDonalds, & Trowbridge, 2013; Schillers, Kendall, Kwak, & Slocum, 2012). These studies indicate that the extent of binocular advantage depends on the difficulty of the manipulation task. For instance, the bead-threading showed more dependence on binocular vision than water pouring task (Piano & O'Connor, 2013). When vision was degraded with lenses, more time was required for threading the large beads (total 37% from median baseline time of 51 seconds), and small beads (0.5%–15% between lenses, total 42% from median baseline time of 57 seconds). However, no significant change in the time required to complete the water-pouring task (the base line time has not changed with using only one lens from 5 to 6 seconds). In the study by Read and colleagues (2013), binocular advantage was calculated as the ratio between the task's outcomes obtained during dominant-eye viewing to that obtained during binocular viewing. Binocular summation was found for the buzz wire task and the peg-board with tweezers task was higher than the peg-board task performed with finger.

The two manipulation tasks used in our research were a peg-board and bead-threading, and the difficulty within each task was manipulated by reducing the size of the pegs and beads. It is important to understand the significance of binocular vision during the performance of fine motor skills that vary in complexity from the rehabilitation point of view. Classification of motor tasks based on the extent of reliance on binocular vision is important in the field of fine motor skills rehabilitation. Occupational and physical therapists should take into account the importance of binocular vision during complex manipulation skills. Because performance of fine motor skills might relate to having abnormal stereoacuity threshold and vergence control, the two latter functions should be assessed before implementing rehabilitation programs. In the cases where abnormal binocular vision is evident, management of binocular vision should be addressed before delivering the rehabilitation program. The status of binocular vison could be an important base for typical development of eye-hand coordination skills. Therefore, determining the significance of binocular vision during complex manipulation tasks will have implication for evaluating and treating disorders causing disturbance of hand functions. For instance, acknowledgement the status of binocular vison during rehabilitation of fine motor skills will make a strong connection between the field of optometry and rehabilitation medicine.

1.2 Thesis objectives

The goal for study 1 of this thesis was to examine age-related contribution of binocular vision to the performance of complex manipulation skills. The second objective for study 1 was to examine the interaction between binocular vision and task complexity. In study 2, the goal was to examine the performance of complex manipulation tasks during binocular and monocular viewing in typically-developing children and children with learning difficulties. The objective of study 3 was to characterize the role of binocular vision in the performance of manipulation tasks involving tool use in visually-normal adults.

Chapter 2: Study 1: Development of Binocular Advantage in Children 5-13 Years Old

2.1 Literature review

Performing movements in our three-dimensional environment requires the ability to localize and discriminate objects accurately. Binocular vision provides important depth cues for planning and execution of reaching and grasping movements (Watt et al., 2003). Monocular depth cues, such as linear perspectives, motion parallax, colours, contrast, shading, and cast shadows also provide depth information (Granrud, Yonas, & Opland, 1985; Oshea, Blackburn, & Ono, 1994; Troscianko, Montagnon, Clerc, Malbert, & Chanteau, 1991; Yonas, Elief, & Arterberry, 2002; Yonas & Granrud, 2006). However, studies have shown that binocular vision provides a unique contribution when planning and executing upper limb reaching and grasping movements (Grant et al., 2014; Suttle et al., 2011; Watt et al., 2003).

The following literature review focuses on the development of both the sensory, and the motor aspect of binocular vision. Binocular vision provides an important cue for depth perception; therefore, the development of depth perception is also considered. Lastly, the developmental trajectory of fine motor skills is discussed in the context of a current theoretical framework of motor control.

2.1.1 Development of binocular visual functions

Binocular vision refers to those functions that involve the cooperative work of both eyes. In this section, the developmental trajectory of sensory and motor aspects of binocular vision, that is stereopsis and vergence, is presented.

Stereopsis, the ability to fuse two slightly disparate retinal images into a single image, is not present at birth. Stereopsis emerges between 3 and 5 months of age (Atkinson & Braddick, 1976; Braddick & Atkinson, 1983; Held, Birch, & Gwiazda, 1980) and continues to develop across childhood. The range of stereoacuity threshold in normal preschool children (3-6 years) is 60-120 seconds of arc. Younger children are less likely to achieve 60 seconds of arc (Afsari, Rose, Shih-I Pai, Gole, Leone, Burlutsky, & Mitchell, 2013; Ciner, Ying, Kulp, Maguire, Quinn, Orel-Bixler, Cyert, Moore, & Huang, 2014). Coarse stereoacuity (i.e., greater than 100 seconds of arc) reaches adult-like level at 4 years of age, whereas adult-like level of fine stereoacuity (i.e. , 6 seconds of arc) is attained later than 14 years of age (Giaschi, Narasimhan, Solski, Harrison, & Wilcox, 2013). Stereopsis provides a relative depth cue for accurate judgment of objects' orientation and relative size and distance in the near environment (McKee & Taylor, 2010). Thus, the development of this system may have important implications for learning of fine motor skills during the childhood period.

The second aspect of binocular vision is ocular vergence, the ability to move both eyes in opposite directions in order to fuse two disparate retinal images into a single percept. As vision needs a cooperative work between the sensory and the motor systems to achieve normal binocular visual function, vergence control may be a precursor for disparity detection (Braddick & Atkinson, 1983). Infants at six months of age are capable of executing convergent eye movements to re-fixate the target upon introduction of 5 and 10 diopter base-in prisms (Aslin, 1977). The period between four and six months is also associated with the emergence of rudimentary reaching movements (Shumway-Cook & Wollacott, 2006). The fine-tuning of vergence eye movements continues throughout the childhood period. For example, Yang, Bucci, and Kapoula (2002) found that vergence latency was longer in children 4.5-10 years old in comparison to adults, and adult-like of vergence latency was attained at 10-12 years of age. In summary, stereopsis and vergence provide important binocular depth cues for the performance of upper limb reaching and grasping movements. However, the developmental trajectory associated with these aspects of vision is prolonged and adult-like level is not attained until the early adolescent period.

2.1.2 Depth discrimination

Stereopsis and ocular vergence provide the basis for binocular depth cues. In addition to binocular depth cues, there are monocular cues that provide some depth information. The ability to use these monocular cues emerges during infancy between five and seven months of age and continues to develop onwards (Ekberg, Rosander, von Hofsten, Olsson, Soska, & Adolph, 2013; Granrud et al., 1985; Van Hof, Van der Kamp, & Savelsbergh, 2006; Yonas, Cleaves, & Pattersen, 1978; Yonas, Pettersen, & Granrud, 1982); however, the ability to use the monocular cues during execution of early reaching movements occurs later than the ability to use binocular disparity cues.

2.1.3 Development of fine motor skills

The following section provides an overview of the development of fine motor skills in the childhood period from 5-12 years of age since this is the age range of interest in the current study. Thus, the focus of this review is on the role of vision in terms of planning and executing reach-to-grasp movements, which have been studied using a motion capture system to quantify the kinematics of the reach trajectory. In order to examine the development of fine motor skills, models of motor control are presented. Lastly, the significance of binocular vision during reach-to-grasp development and during the performance of complex manipulation skills is discussed.

2.1.3.1 Models of limb control

According to the Woodworth's model (1899), the trajectory of reaching movements consists of two phases: the initial adjustment phase and the current control phase. The initial adjustment phase involves ballistic control, which means that it is performed without processing of sensory information related to the movement. Current control phase includes a low-velocity approach to the target controlled by sensory feedback which can be used to execute corrective sub movements to ensure that the target is acquired. Elliot, Hansen, Lawrence, Grierson, Simon, and Spencer (2010) expanded this simple model of limb control by proposing that there are multiple processes occurring during the two phases that were identified by Woodworth (1899). Elliot's Multiple Processes Model of limb control is centered on the concept of the internal model, which is a representation or a simulation of a sensory-motor transformation for a motor behaviour in a given context. The internal model consists of an efferent copy of the motor commands sent to the muscles and the prediction of the expected sensory consequences of the movement. Elliott proposed that there are two online control mechanisms activated during movement execution: early online control and late online control. First, early online control is based on the activation of the internal model, which uses the efferent copy to simulate the movement and predict the outcome. If discrepancy is detected between the desired and the simulated outcome, adjustment to the movement trajectory can be initiated even before sensory information is acquired and processed. The second process involves late online control, and it is based on the comparison between early movement-related feedback and the anticipated sensory consequences. It has been hypothesized that development of optimal motor control involves predictive control and the ability to correct movements quickly during execution. According to the multiple processes model, this ability requires early online control that relies on the internal model. In order to engage the early online control processes, the internal model must be accurate and precisely calibrated to ensure that the predictions of the impending actions are accurate. The development of an accurate internal model of motor control will depend on the reliability of the sensory information during development and learning. In particular, binocular visual input might provide an important signal to calibrate the internal model for motor coordination. However, the role of binocular vision in learning new tasks or in the development of motor control is currently unknown. Given that binocular vision and eye-hand coordination skills develop in parallel lines, the next section examines the development of fine motor skills.

2.1.3.2 Developmental aspect in reaching and grasping

Fine motor skills involve a variety of movements such as reaching, grasping, and manipulating objects. The ability to process sensory information during the movement planning and execution (i.e., online control) has been studied while manipulating the sight of the hand and/or the target (Hay, 1979; Kuhtz-Buschbeck, Stolze, Jöhnk, Boczek-Funcke, & Illert, 1998; Rosblad, 1997; Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002; Smyth, Peacock, & Katamba, 2004). Movement kinematics obtained using high speed motion capture systems provide an insight about reach and grasp planning. For example, peak velocity and peak grip aperture represent the planning aspect of reaching and grasping, respectively. The deceleration phase represents the interval when sensory information is processed online until the target is contacted or picked up (Elliot et al., 2010; Grant et al., 2014; Kuhtz-Buschbeck et al., 1998; Suttle et al., 2011; Watt et al., 2003). Research in the area of developmental motor control has established important age-related differences in visuomotor coordination in school-aged children. For example, Hay (1979) examined pointing movements toward a visual target and found that children younger than 7 years old performed pointing movements using ballistic control (i.e., similar to the initial adjustment phase in Woodworth two-component model). In contrast, children older than 7 years old began to utilize visual feedback during movement execution. Children between 9 and 12 years were capable of integrating the ballistic approach and visual guidance during deceleration phase (i.e., corrective sub movements occurs during the movement).

Kuhtz-Buschbeck and colleagues (1998) examined reach-to-grasp movements while visual feedback was manipulated (i.e., full vision and no vision as the light was turned off at the start signal). In children younger than 7 years old, half of the movement time was spent in the deceleration phase, in contrast, 7- and 12 year-old children had a prolonged deceleration phase. Age-related increase in the percentage of time spent in the deceleration phase indicates an improved ability to process sensory information during movement execution (Kuhtz-Buschbeck et al., 1998). Results of Kuhtz-Buschbeck and colleagues (1998) further built on the results of

Hay (1979) since children older than 7 years began to incorporate sensory information during the movement, they were more dependent on the availability of visual information of the hand and target. Several researchers have postulated that these improvements in motor control emerge when children learn to rely on the predictive control (Babinsky, Braddick, & Atkinson, 2012; Conteras-Vidal, Bo, Boudreau, & Clark, 2005). Current theoretical and experimental findings suggest that this type of predictive control requires a well-calibrated internal model (Sabes, 2000; Shadmehr, Smith, & Krakauer, 2010: Wallace, Chandler, Beck, Arnold, Bacal, & Birch, 2007; Wolpert, 2007), that is, an internal representation of the sensory-motor transformation of the action in a given environment. Thus, development of reaching and grasping movement is based on the ability to utilize predictive control which requires a calibrated internal model for movement control.

For the grasping component, predictive control is also evident in grip aperture formation and grip force application. With respect to grip aperture, children as young as 4 years old were able to scale their grip size depending on the target's size when visual feedback was provided (Kuhtz-Buschbeck et al., 1998). On the other hand, when vision was occluded at movement initiation, young children lacked the ability to adjust grip aperture to object's size, which was in contrast to the oldest group of children who were 11-12 years old. The oldest group of children programmed their grip aperture based on the information acquired before the occlusion of vision which indicates that they developed the ability to utilize predictive control during movement execution. It was concluded that children older than 12 years are capable of producing an adult-like reaching behaviour, which relies on predictive control (Kuhtz-Buschbeck et al., 1998). Grip force is the amount of force required to grasp an object, whereas lift force is the amount of force needed to pick up an object. The ability to generate grip force using a single burst of force scaled to the object's characteristics is not well-developed in 9-year-old children because they dropped the object when they were lifting it up (Pare & Dougas, 1999). In conclusion, the ability to process and use visual information to execute accurate reach-to-grasp movement and to generate adequate grip force develops during early adolescence period.

2.1.4 The significance of binocular vision during development of reach-to-grasp movements and complex manipulation skills

Given that both binocular vision and fine motor skills develop in parallel, an important question in developmental neuroscience is to examine the role of binocular vision in the development of the fine manipulation skills in visually-normal children. Individual studies have shown that visuomotor coordination and binocular vision continue to improve in typically-developing children between birth and early teenage years, however, no study has systematically addressed the relationship between the development of binocular vision and fine manipulation skills. There are only three studies in the literature that investigated the effect of age on binocular advantage (i.e., improvement in task performance during binocular viewing compared to monocular viewing) during reach-to-grasp movement using the kinematic approach (Grant et al., 2014; Suttle et al., 2011; Watt et al., 2003). The paper by Watt and colleagues (2003) is the only one that focused on visually-normal children (5-6, and 10-11 years old). Results showed age-related differences between the younger and older group in the kinematic parameters of a reach-to-grasp movement during binocular and monocular viewing. While both groups of children had slower movement initiation and earlier production of peak grip aperture during monocular viewing, only the older group of children spent a longer time in the deceleration phase under monocular viewing. In contrast to older children, the younger group of children could not scale their grip aperture to object size during monocular viewing. Thus, it was concluded that in case of the older children, binocular vision is more important during online movement control where inaccurate information about object's properties can be corrected by extending the deceleration phase. In the case of younger children, their reaching movements were characterized by ballistic movement, and there was no evidence that binocular vision was used during movement execution.

Both Shuttle et al. (2011) and Grant et al. (2014) included healthy children as a control group and compared their performance to children with abnormal binocular vision. Results from these studies showed that children younger than 7 years had a reduced ability to utilize monocular depth cues for movement planning, but their movement duration was similar in both viewing conditions. Children between 7 and 9 years old benefitted from binocular vision mostly in the planning aspect. For example, they spent a longer time in planning their movements, had less ability to scale their peak velocity in relation to target's location, and were less able to adjust their grip size in relation to the target's size during monocular viewing. On the other hand, 9 to 12 year-old children had a greater binocular advantage. They spent longer time processing sensory information in the later stage of movement before contacting and grasping the object during monocular viewing, a behaviour that was similar to that of adults. One interpretation of these experimental results is that binocular vision is particularly important for planning and execution of accurate goal-directed movements when children are learning to use sensory feedback to guide online correction during movement execution. Even though these studies provide some evidence for the significance of binocular vision during reach-to-grasp movement, a relatively simple task was used. The development of binocular advantage during execution of complex manipulation tasks has not been studied in visually-normal, primary school-aged children, yet. Studying age-related contribution of binocular vision during performance of simple tasks does not provide a complete developmental trajectory for the role of binocular vision during the performance of fine motor skills. Investigating the effect of removing binocular visio during complex manipulation tasks is also important because these tasks are more reflective of children’s activities during play and at school. Thus, peg-board and bead-threading tasks were chosen for this study because they require good eye-hand coordination as well as sequential movement planning. Children have to plan their first movement to grasp the bead or the peg and then to place the bead or the peg in a specific location (i.e., the hole in the case of the peg-board task and the needle in the case of the bead-threading task). Furthermore, clinicians use these tasks to assess fine motor skills development. For example, both tasks are part of the Bruininks-Oseretsky Test of Motor Proficiency and the Movement Assessment Battery for Children. Understanding the significance of binocular vison during the performance of these tasks will provide insight into interpreting the results obtained from the motor assessment. For example, if binocular vision provides important input during the performance of these tasks, impairment on these tasks might be partially caused by disorders of binocular vision that needs to be diagnosed and treated.

Two outcome measures used to quantify the performance on the peg-board and the bead-threading tasks during binocular and monocular viewing were movement time and the binocular summation defined as the ratio in movement time between binocular and monocular viewing conditions. Movement time was used because it is a measure frequently employed to quantify the overall performance of motor tasks. Binocular summation is an outcome measure used to quantify the relative advantage offered by binocular viewing in comparison to monocular viewing on individual basis. Binocular summation has been commonly used to quantify the binocular advantage for other visual functions. For example, studies have shown a binocular advantage of 1.14 for visual acuity (Banton & Levi, 1991) and contrast sensitivity (Baker, Meese, Mansouri, & Hess, 2007). This means that sensitivity improves during binocular viewing compared to monocular viewing. Only the study of Read and colleagues (2013) used the binocular summation to directly compare motor performance during binocular and monocular viewing in adults. Thus, this study is the first one to examine binocular summation during performance of complex manipulations tasks in children.

2.1.5 Research objectives and questions

The overarching objective of this thesis was to investigate the role of binocular vision in the performance of manipulation skills in children between 5 and 13 years old. Three research questions were addressed in this study:

1- What is the effect of age on the performance of the bead-threading and peg-board tasks across binocular and monocular viewing conditions?
2- Does the significance of binocular vision vary with task difficulty?
3- What is the effect of age and stereoacuity on the binocular advantage?

2.1.6 Hypotheses

1. Movement time will decrease significantly with age during both monocular viewing and binocular viewing in both manipulation tasks.

2. Binocular advantage will be significantly greater in the bead-threading task in comparison to the peg-board task because bead-threading task requires a greater precision in object alignment.

3. Binocular advantage should increase with age and should be lower with low stereoacuity threshold.

2.2 Method

2.2.1 Participants

Fifty-eight children between 5 and 13 years old were recruited (26 boys, 32 girls). Children were recruited from a local summer and winter camps or from the Kitchener-Waterloo community. Children were further divided into three age groups based on their age: young: 5- <7 years (n=20, 12 girls and 8 boys), middle: 7- <10 years (n=19, 12 girls and 7 boys), and old: 10-13 years (n=20, 8 girls and 12 boys). These age groups were chosen based on research which showed that children's visuomotor control changes significantly at these ages. A control group consisted of 20 healthy adults who were tested in order to compare the performance between the developing system (children) and the developed system (adults). Adults were recruited from the Department of Kinesiology in the University of Waterloo (17-38 years old: 12 women and 8 men). This study was approved by the Office of Research Ethics at the University of Waterloo. Both adults and parents gave consent prior to participation. Children signed an assent form.

2.2.2 Experimental procedure

The experimental procedure consisted of two components: assessment of visual functions, namely visual acuity and stereoacuity, and assessment of manipulation skills, namely the peg-board task and the bead-threading task.

2.2.2.1 Assessment of visual acuity

Visual acuity was tested using a forced choice, four-alternative, descending method of limits (i.e., staircase) to determine the threshold for optotype discrimination. The staircase was implemented using VPixx software. Participants were seated at a distance of 2.5 m away from the monitor (19 in Samsung, CRT, resolution 1024x780, refresh rate 60 Hz). A white letter "E" was presented on a black background in the center of the monitor. Participants had to determine the direction of the arms of the letter "E" (i.e., up, down, left or right). Four animal stickers wee placed on the frame of the monitor to help children decide which way the letter "E" was facing. Younger children were also asked to point with their index finger to indicate which way the open arms of the letter "E" were facing. The first letter was 20 min of arc, the size of the letter was reduced progressively after three correct responses and increased after each incorrect response. The step-size for the staircase was 0.1 log min arc. The staircase terminated after 6 reversals and acuity threshold was defined as the average of the last four reversals. Visual acuity was assessed both binocularly and monocularly for each eye.

2.2.2.2 Assessment of stereoacuity threshold

Stereoacuity thresholds were determined using the Randot Stereo-acuity test. Participants were seated in a chair and viewed a book containing shapes, such as circles or animal pictures. The test was performed at a 40 cm distance, as recommended in the instructions. Participants wore glasses with polarized lenses to dissociate the input to each eye. Some of the shapes appeared to be popping-out of the page and the participants' response was to indicate which shape is coming out of the page. This test provides the threshold for the participants' ability to combine the images from both eyes (i.e. the stereoacuity threshold).The stereoacuity threshold was determined as the smallest disparity that was reported correctly.

Based on the assessment of visual acuity and stereoacuity, participants were included in the study only if they had normal or corrected-to-normal binocular and monocular visual acuity (i.e., at least 0.1 logMAR and interocular acuity difference less than 0.2 logMAR) and normal stereoacuity threshold according to age norms (i.e., better than 100 arc sec for children and better than 40 seconds of arc for adults) (Birch, Williams, Drover, Fu, Cheng, Northstone, Courage, & Adams, 2008). Participants were excluded if they had a history of amblyopia or strabismus. Overall, six children (i.e., two girls and two boys from the 5-6 year-old group, two boys from 7-9 year-old group) and a female adult were excluded.

2.2.2.3 Assessment of manipulation tasks

Before testing the manipulation tasks, the Edinburgh Handedness Inventory scale was administered in order to determine hand preference (Oldfield, 1971). Children were asked to indicate verbally the preferred hand during performance of manual activities and tool use, or to demonstrate the action with their preferred hand. Hand preference was determined by the scores; participants achieving score >+40 were considered right-handed, <-40 were considered left-handed, scores between -40 and +40 were considered ambidextrous. All experimental manipulation tasks were performed with the participant's preferred hand. Fifty-one children performed level 1 of the bead- threading task; fifty-two children performed level 2 of the bead-threading task. Fifty-two performed level 1 of the peg-board task, and fifty-one performed level 2 and 3 of the peg-board task. Mean age, hand preference, and stereoacuity across groups are presented in Table 1. All manipulation tasks were performed during three viewing conditions. A black eye patch was used to block vision during monocular viewing. The order of the tasks and viewing conditions were randomized as follows: the order of the tasks was first randomized using the RAND functions in Excel (Microsoft Office, 2010). Within each task, the levels of difficulty were randomized, and within each level of difficulty the viewing condition was randomized. Participants were instructed to complete each task as quickly and accurately as possible using their dominant hand, while holding the other hand on their lap. Practice trials were performed before each task until the participants were confident with their performance.

Table 2.1: Mean age, hand preference, and stereoacuity thresholds for the different groups

Group	N	Age (years)	Hand preference	Stereoacuity (seconds of arc)
Young **5-<7 year**	17	6.00±0.5	64.7% right-handed 11.8%left-handed, 23.53%ambidextrous	20-70
Middle **7-<10 years**	17	8.4±0.9	82.35% right-handed 5.88% left-handed 5.88% ambidextrous	20-70
Older **10-13 years**	19	11.5±0.9	84.21% right-handed 10.53% left-handed 5.26% ambidextrous	20-30
Adults	19	24±5	89% right-handed 11%ambidextrous	20-50

2.2.2.3.1 Bead-threading task

A vertically mounted needle was placed 40 cm from the participant’s sternum. The two sizes of beads (small: diameter= 0.7 cm and large: diameter= 1 cm) were placed in a standardized location 30 cm from the participants’ preferred hand. Participants were instructed to pick up the correct bead and to place it onto a blunt needle mounted vertically on a piece of wood. The task involved picking up 10 beads and placing them onto the needle one at a time (see Figure 2.1). The diameter of the hole was 0.5 cm and it was the same for both bead-sizes. The main outcome measure was movement time which was defined as the time elapsed between picking up the first bead and successfully placing the last one onto the needle. Movement time was measured with a stop watch.

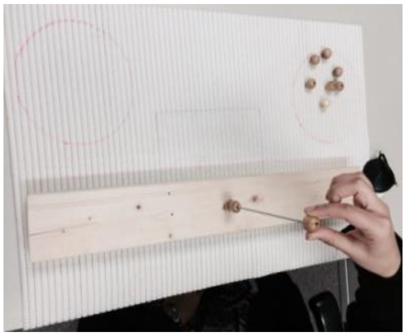


Figure 2.1: Bead-threading task where participants insert ten beads of one size into a vertically-mounted needle under three randomized viewing conditions (binocular, left-eye monocular, and right-eye monocular viewing conditions).

2.2.2.3.2 Peg-board task

Participants were asked to pick up a peg that matched the size of the holes in each board and insert it into the hole (see Figure 2.2). The board was a custom-made 6x6 cm with the holes arranged in a 3x 3 pattern, the separation between the hole was 5 cm. The board was placed 30 cm from the edge of the table, aligned with participants' midline. All pegs (length 3.7 cm) were placed in a standardized location 30 cm from the participants’ preferred hand. To manipulate the difficulty of the task, three peg sizes were used: small (diameter= 0.3 cm), medium (diameter=

0.6 cm) and large (diameter= 0.9 cm). Movement time for each task was measured with a stop watch and defined as the time between picking up the first peg and successfully inserting the last one.

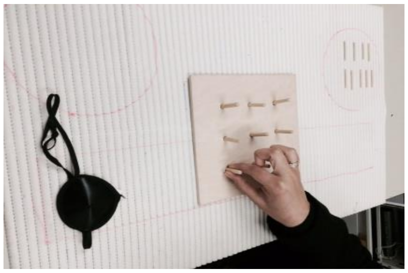


Figure 2.2: Peg-board task where participants match the size of nine pegs ad insert them into the holes of the board under three randomized viewing conditions (binocular, left-eye monocular, and right-eye monocular viewing conditions).

2.2.3 Analysis

The first question of this research was to examine the effect of age on performance of the bead-threading and peg-board tasks. This question was examined using a mixed model analysis of variance (ANOVA). Before running the ANOVA on movement time, a paired t- test was conducted to compare movement time during left-eye and right-eye viewing. Results showed no significant difference between the left-eye and right-eye viewing conditions (p=0.7 for the bead-threading and p=0.1 for the peg-board task). Because there was no significant difference between the left and the right-eye monocular viewing conditions, the data were collapsed and the average of both monocular viewing conditions was used for further analysis. The between subject factor was Group (young: 5-<7 years old, middle: 7-<10 years old, older:

10-13 years old, and adults). The two within-subjects factors were Viewing Condition (binocular and monocular) and Target Size (large and small for bead-threading task and small, medium, and large for the peg-board task). The dependent variable for this analysis was movement time. A separate ANOVA was conducted for each task.

The second research question was to determine whether the significance of binocular vision varies during the performance of bead-threading and peg-board tasks. The binocular summation, defined as the ratio of movement time during binocular viewing and monocular viewing, quantifies the individual's advantage during binocular viewing in comparison to monocular viewing in each task and target size. Mean binocular summation was compared between the bead-threading and peg-board tasks using an ANOVA. The between-subject factor was Group (young, middle, older, adults). The two within-subjects factors were Task (bead-threading, peg-board) and target size (large and small). For ease of comparison, only two levels of the peg-board task were used. The level with small pegs was removed since there was no comparable bead size in the bead-threading task.

The third question was to examine the effect of age and stereoacuity on the performance of complex manipulation skills in children. In order to normalize the stereoacuity data, stereoacuity thresholds measured in seconds of arc were transformed to log-base 10 scale. The log base 10 of stereoacuity was used for correlation and regression analysis. Regression analysis was conducted with age and stereoacuity as predictors. All statistical analyses were performed using the SAS 9.4 software package. Descriptive statistics are reported as the mean and corresponding standard deviation. Any main effects and interactions were analyzed further using Tukey-Kramer post-hoc tests to adjust for multiple comparisons. The significance level was set at $p < 0.05$.

2.3 Results

2.3.1 Age- and task-related effects on movement time

2.3.1.1 Bead-threading task

Mean movement time in the bead-threading task during binocular and monocular viewing is shown in Figure 2.3A. Results from the statistical analysis for main effects of Group, Viewing Conditions, and Target Size are reported in Table 2.2. The main effect of Group indicates that performance improved with age, performance was also faster during binocular viewing compared to monocular viewing, and when the task was performed with large beads compared to small beads. The central question of this research was to determine if the contribution of binocular vision changes with age, which was supported by a significant interaction between Group and Viewing Condition ($F_{6,67}=5.9$, $p=0.001$). As illustrated in Figure 2.3A and confirmed by a post-hoc test, movement time during binocular viewing was comparable between the older group of children (22.89±3.35 s) and adults (22.10±4.11 s). Older group had significantly shorter movement time in comparison to the middle group (26.67±4.97 s) and the young group

(37.27±11.91 s). The latter two groups were also significantly different from each other. Post-hoc test also revealed that movement time was significantly different among all the groups during monocular viewing (young: 47.78±11.64 s; middle: 35.61±6.95 s; older: 30.33±5.95 s; adults: 26.59±4.71 s). As shown in Figure 2.3A and confirmed by post-hoc tests, the difference in movement time between binocular and monocular viewing was greatest in the young children (10.44 s), reduced in the middle (8.98 s) and the older groups (7.44 s), and smallest in the adults (4.00 s). There was a significant interaction between Group and Target Size ($F_{3,66}$=6.82, p=0.0004). Post-hoc tests revealed that the effect of changing the bead size was greater in the young (6.57 s) and the middle groups (4.41 s) in comparison to the older group (0.76 s) and the adults (2.98 s) (see Figure 2.4A). The three-way interaction between Group, Viewing Condition, and Target Size was not significant ($F_{4,66}$=0.82, ns). Therefore, facilitation of performance during binocular viewing was evident in all age groups, however, removal of binocular vision resulted in relatively longer movement times in children than in adults.

2.3.1.2 Peg-board task

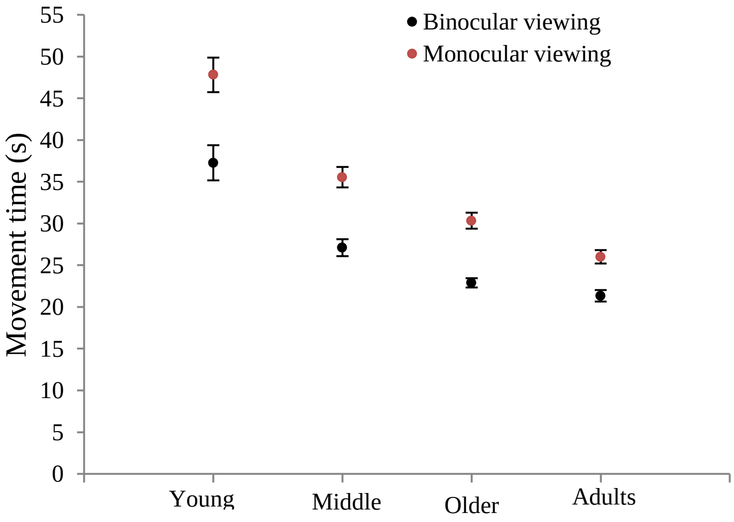
Results for the peg-board task showed a main effect of Group, Viewing Condition, and Target Size (see Table 2.2 for the results of the statistical analysis). Similar to the bead-threading task, performance improved with age, during binocular viewing in comparison to monocular viewing, and when manipulating the large pegs in comparison to the medium and small pegs.

Similar to the bead-threading task, the interaction between Group and Target Size was significant ($F_{6,132}$=9.42, p<0.0001); Figure 2.4B. In contrast to the bead-threading task, the interaction between Group and Viewing Condition was not significant ($F_{3, 66}$=0.56, ns). The absence of the interaction in the peg-board tasks suggests that the effect of viewing was similar across groups. In contrast to the bead-threading task, performance in the peg-board task showed less improvement during binocular viewing in comparison to monocular viewing.

Table 2.2: Statistical results for the main effects and interaction effects in the bead-threading and peg-board tasks

	Bead-threading task	**Peg-board task**
Group	$F_{3,67}$=31.5, p<0.0001	$F_{3,67}$=24.06, p<0.0001
Viewing	$F_{1,67}$=217.5, p<0.0001	$F_{2,67}$=46.41, p<0.0001
Level	$F_{1,66}$=56.83, p<0.0001	$F_{2,66}$=57.92, p<0.0001

A.



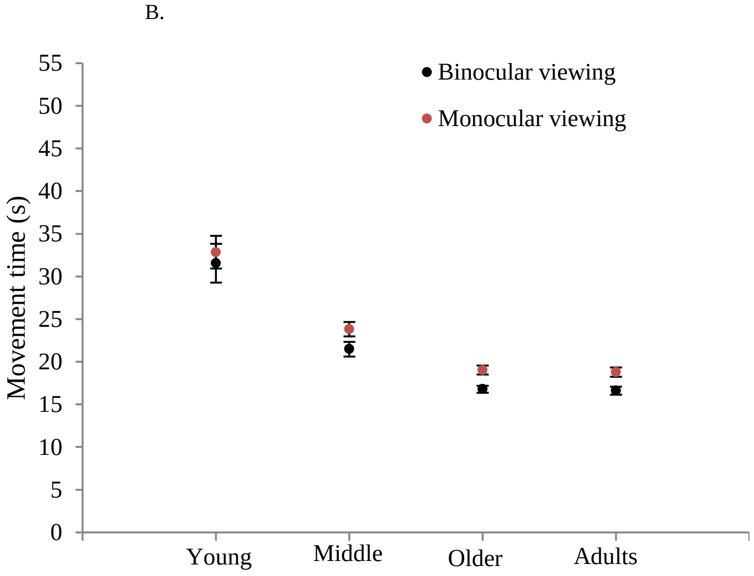
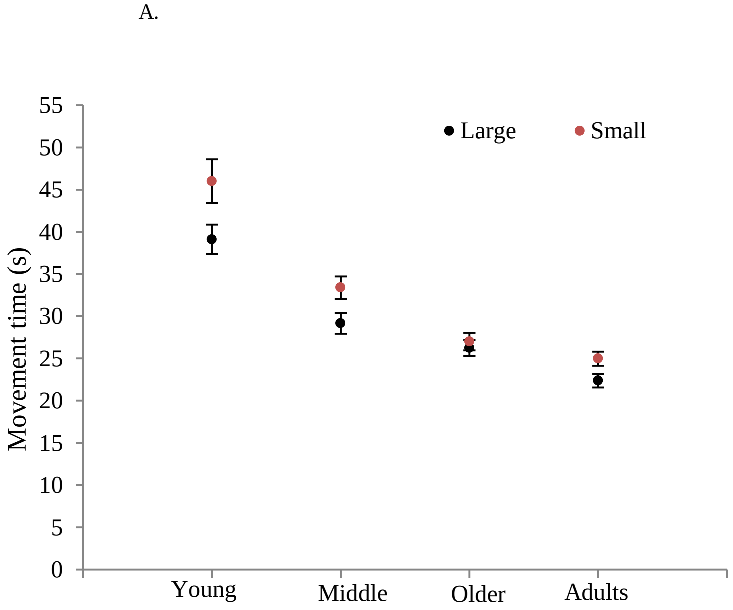


Figure 2.3: Mean movement time to complete the bead-threading task (A) and the peg-board task (B) plotted for the different age groups during binocular and monocular viewing.



B.

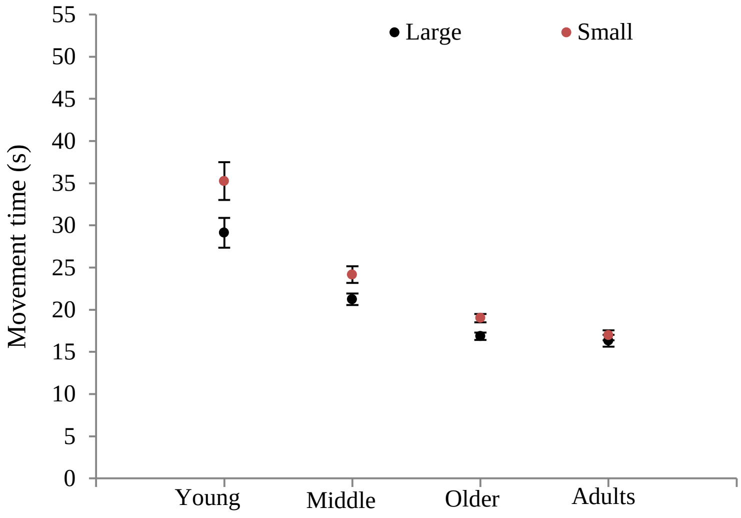


Figure 2.4: Mean movement time to complete the bead-threading task (A) and the peg-board task (B) plotted for the different age groups using two different target sizes.

2.3.2 Age and task-related effects on the binocular summation

The second research question was to examine whether the significance of binocular vision varies with task difficulty. Binocular summation was used to compare binocular advantage between the bead-threading and peg-board tasks. In addition to the significant main effect of task ($F_{1,67}$=77.65, p<0.0001), the interaction between Group and Task was also significant ($F_{3,67}$=2.81, p<0.05). As illustrated in Figure 2.5, children had a lower binocular summation in comparison to adults, for the bead-threading task in comparison to the peg-board task. The lower binocular summation in the bead-threading task indicates a higher binocular advantage in comparison to the peg-board task. Thus, binocular advantage was significantly higher in the bead-threading task in comparison to the peg-board task as indicated by a lower binocular summation (0.79±0.12 vs. 0.92±0.16). The lower binocular summation in children indicates that they were relying relatively more on binocular vision to complete this task in comparison to adults. Overall, the binocular summation differed across tasks and between children and adults.

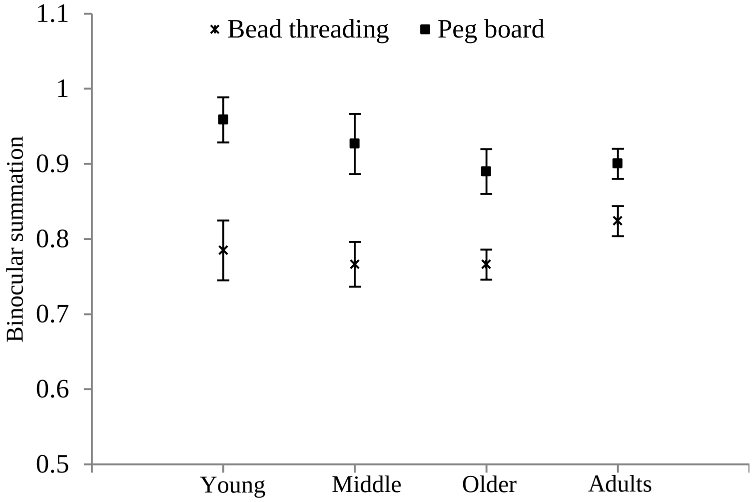


Figure 2.5: Mean binocular summation ratio for the bead-threading and peg-board tasks plotted across the age groups.

2.3.3 Relation between age, stereoacuity, and binocular advantage

The range of stereoacuiy in children was between 20 and 70 seconds of arc. A correlation analysis was conducted to examine the association between age and stereoacuity. A significant negative correlation was found between stereoacuity and age (Pearson's r = -0.38, p=0.005) (see Figure 2.6A). The effect of stereoacuity on the performance of the bead-threading task was examined using a multiple linear regression analysis. Bead-threading task was chosen because it had a lower binocular summation compared to the peg-board task. The lower the binocular summation, the greater the difference in movement time between binocular and monocular viewing; thus, the greater the binocular advantage. Since the research question is to examine age-related changes in binocular advantage in visually-normal children, adults' data was excluded.

2.3.3.1 Bead-threading task

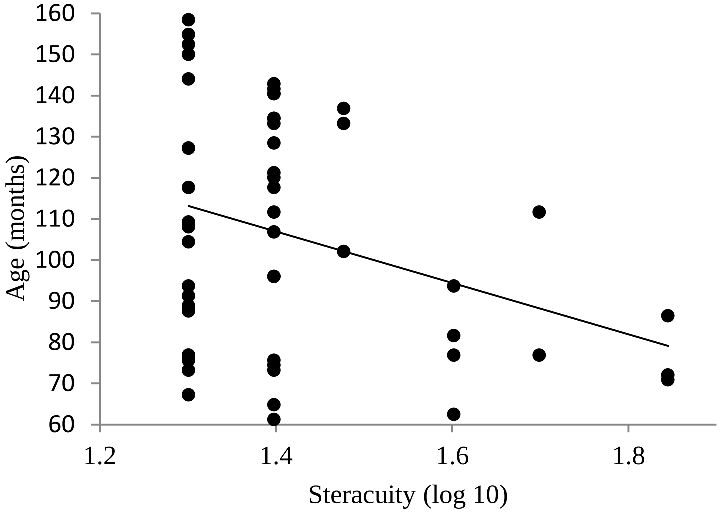
Results from the stepwise regression for the bead-threading task showed a 9.8% of variance explained by stereoacuity alone (p=0.023). However, the regression estimate for stereoacuity was negative (slope: -0.20143: intercept: 1.05631; Figure 2.6B). This indicates that children with higher stereoacuity thresholds (i.e., range 50-70 seconds of arc) had a lower binocular summation in comparison to children with a lower thresholds (i.e., range 20-30 seconds of arc).

Thus, performance in the bead-threading task was less disturbed during monocular viewing in children with stereoacuity between 20-30 seconds of arc (i.e., small difference in movement time between monocular and binocular viewing). On the other hand, children with lower stereoacuity thresholds had a higher binocular summation, which indicates a smaller relative difference between movement times during binocular and monocular viewing. Overall, binocular summation was associated with stereoacuity on the bead threading task (see Figure 2.6B); however, there was no significant effect of age (see Figure 2.6C).

2.3.3.2 Peg-board task

Age was the only significant predictor for the binocular summation in the peg-board task, explaining 9% of variance (p=0.03). As expected, the regression estimate for age was negative (age: -0.001; intercept: 1.027), which means that younger children had a higher binocular summation. Younger children had a smaller relative difference in movement time between the binocular and monocular viewing conditions. Older children had a greater relative difference in movement time between binocular and monocular viewing (see Figure 2.7A). In contrast to the bead-threading task, stereoacuity was not a significant predictor for the binocular summation in this task (see Figure 2.7B). Overall, age and stereoacuity are the two significant predictors for binocular advantage in the peg-board and bead-threading tasks, respectively.

A.



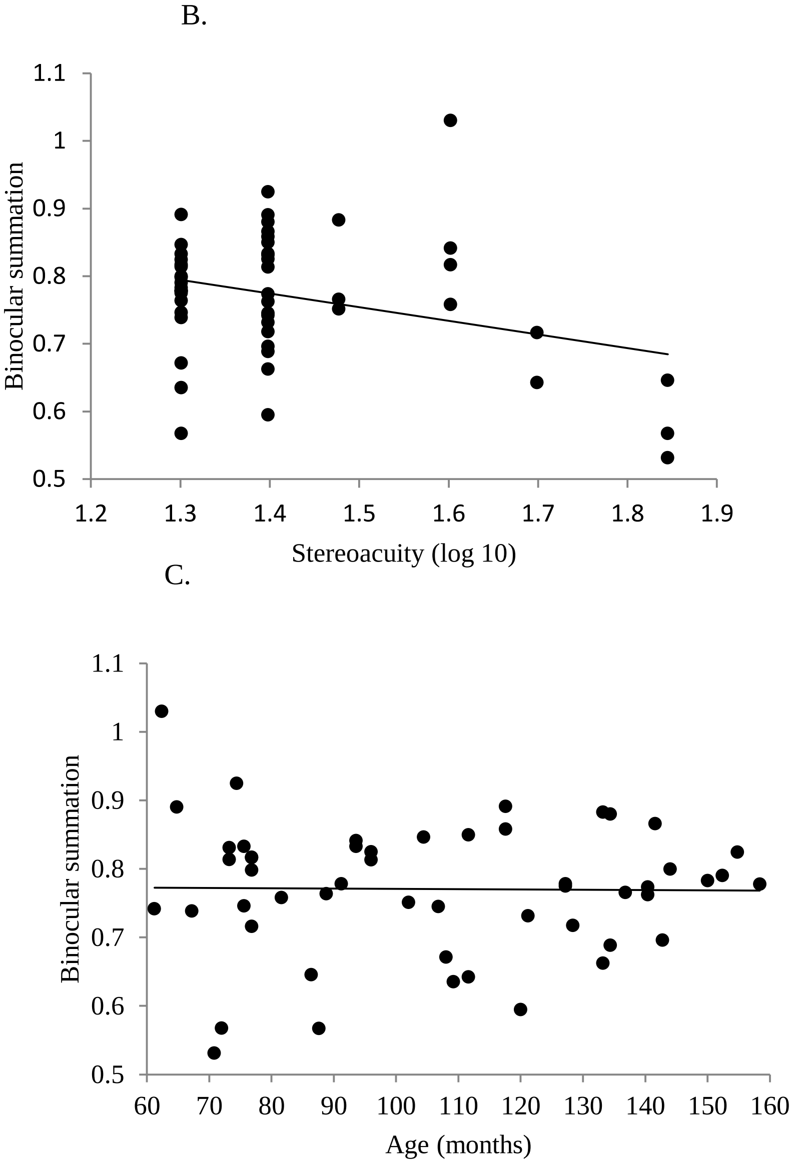


Figure 2.6: Association between stereoacuity and age (A) and between stereoacuity and binocular summation (B) for the children data (C) and between age and binocular summation for the bead-threading task.

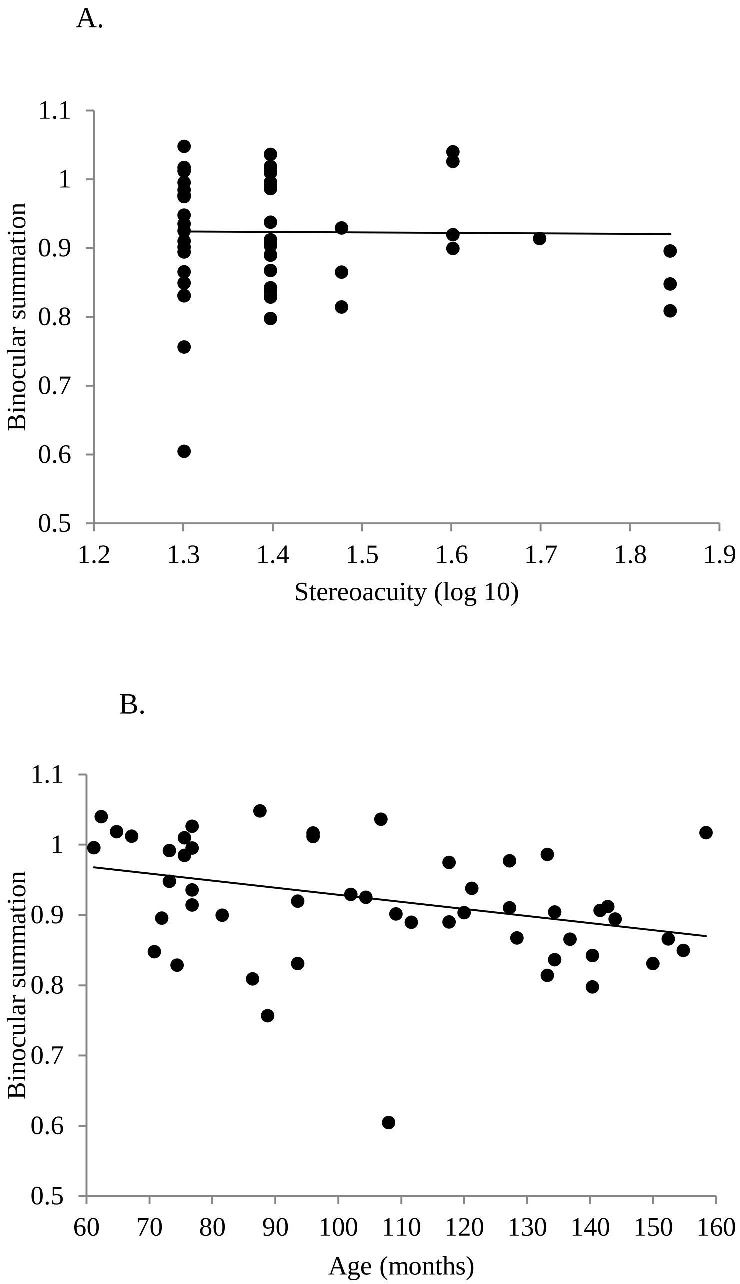


Figure 2.7: Association between (A) age and binocular summation (B) and between stereoacuity and binocular summation for the peg-board task for the children data.

2.4 Discussion

The aim of the current study was to examine age-related contribution of binocular vision during performance of complex manipulation tasks in visually-normal children. The main finding of this study is that the contribution of binocular vision is highly dependent on the age and on the task. Binocular advantage was evident in all groups of children and adults during performance of the bead-threading task. In contrast to the bead-threading task, binocular advantage was significantly lower in the peg-board task.

2.4.1 The effect of age and viewing conditions on the performance of complex manipulation tasks

The first hypothesis for this study was that movement time will decrease significantly with age; and that movement time during monocular viewing will be significantly higher in comparison to the binocular viewing in all age groups in both manipulation tasks. The results are in line with this hypothesis since mean movement time during binocular and both monocular viewing decreased with age in both tasks. The older group of children was similar in terms of movement time to the adults during binocular viewing, but their performance was different during monocular viewing. In the peg-board task, the older group of children showed a similar performance to that of adults in both viewing conditions. In contrast to the bead-threading task, the difference between binocular and monocular viewing was similar in all groups in the peg-board task, suggesting that the effect of viewing on the peg-board task was smaller. Interestingly, the difference in movement time between binocular and monocular viewing reduced with age. In the bead-threading task, the younger group had the greatest increase in movement time during monocular viewing (10.45 s). Because the effect of age was not significant for the binocular summation in children, binocular advantage was evident in all groups, a finding which contrasts previous studies which showed that binocular advantage was greater in children older than 7 years. The discrepancy in results could be due to the different in the type of the task used. Previous studies have utilized reach-to grasp for a single object, whereas complex manipulation tasks were used in our study. The binocular summation was lower in all age groups (young: 0.78; middle: 0.76; older: 0.77) than in adults (0.83), revealing age-related difference in binocular advantage. Children of all age groups were more affected by the removal of binocular vision than adults. Based on this finding, one might speculate that the ability to utilize monocular depth cues is still not developed even in 10-13 year-old children.

Our results can be interpreted in the context of the internal model for movement control framework. The internal model represents a sensory-motor transformation for a motor behaviour in a given context. The internal model consists of an efferent copy of the motor commands sent to the muscles and the prediction of the expected sensory consequences of the movement. Thus, prediction of the sensory consequences via the internal model allows early online control which means that movement trajectory can be adjusted before movement-related sensory information is acquired and processed. Numerous studies with adults support the idea that movement execution relies on predictive control, which involves a precisely calibrated internal model. Thus, motor development involves fine-tuning of the internal model based on sensory input. Because adults have developed this internal model of motor control, the binocular advantage was lower than that of children in all age groups. Since children between 5 and 13 are still developing the internal model, they have relatively more prolonged movement time during monocular viewing compared to binocular viewing. Because children depend more on the availability of binocular vision than adults, the relative difference in movement time between binocular and monocular viewing was greater in children than in adults. Therefore, binocular vision might be important for optimal development of fine motor skills.

Because adult-level of stereoacuity and vergence control is not attained until early teenage years, the maturation of the binocular visual system may be a prerequisite for optimal development of fine motor skills. Both stereopsis and ocular vergence are important for effective execution of reaching and grasping movements. For example, fine stereoacuity provides relative depth information, which is important for determining an object’s characteristics such as shape and texture. Having healthy binocular vision provides a more accurate representation of the surrounding environment and thus leads to more accurate planning and execution of movements.

The age-related improvement in task performance demonstrated in our study may be linked to improvement in stereoacuity thresholds. We found a significant improvement in stereoacuity with age in our sample; we also found a significant association between stereoacuity and binocular advantage for the bead-threading task. Having lower stereo-sensitivity was associated with a lower binocular summation, and higher stereo-sensitivity was associated with a higher binocular summation. This finding could be interpreted in the context of the internal model framework for motor control. Specifically, normal binocular vision and low stereoacuity threshold could lead to a more precisely calibrated internal model, which allows participants to perform accurate movement even when binocular vision is removed. In people with lower stereo-sensitivity (i.e., higher thresholds), the prediction of the expected sensory consequences might be less accurate. Therefore, removal of binocular vision results in a greater disturbance of the movement. In other words, movement time will be increased to a greater extent during monocular viewing in children with higher stereoacuity threshold. However, one limitation of this study is that these findings are based on a relatively small number of children with higher stereoacuity threshold (i.e., 50 – 70 seconds of arc).

2.4.2 The effect of tasks on the binocular advantage

Results from this study are in agreement with previous studies which showed that the role of binocular vision in motor performance varies across manipulation tasks (Piano & O’Connor, 2013; Read et al., 2013). When comparing the two tasks used in this study, significant increase in the movement time during monocular viewing was found in the bead-threading task, regardless of age. The effect of viewing condition was similar across groups (average 2 seconds) in the peg-board task, compared to 6-10 seconds difference between the two viewing conditions in the bead-threading task. Such results might imply less sensitivity of the peg-board task to the removal of binocular vision. The reduced sensitivity of the peg-board task was further confirmed by the binocular summation, which gives a better estimation of the individual's binocular advantage. The binocular summation was comparable in all groups in the peg-board task between 0.9-1, suggesting that participants had similar movement time when completing the peg-board task viewing with one or both eyes. In contrast, the binocular summation ranged between 0.75- 0.85 for the bead-threading task. The lower the binocular summation is, the greater the binocular advantage for a given task. The significant effect of task on the binocular summation clearly distinguished the dependence on binocular vision during the performance of the bead-threading and the peg-board tasks. This finding is in agreement with that of Read and colleagues (2013) and Piano and O'Connor (2013), who tested mainly adults. The importance of binocular vision for the performance of the bead-threading task was further confirmed by a significant association between stereoacuity and the binocular summation in the bead-threading task, but not in the peg-board task.

Overall, binocular advantage was different between the two tasks used in this study. In the bead threading task, participants inserted ten beads onto a vertically mounted needle, whereas in the peg-board task, participants matched the size of nine pegs to the hole of the board. Two potential factors that might contribute to the difference in the binocular advantage between the two tasks are the size and shape of the target and the precision level for target placement. Even though the size of the beads (1 cm, 0.5 cm) was comparable to the size of the pegs (0.9 cm, 0.6 cm), the grasp requirement is different in both targets. Because the shape of the peg is cylindrical, it can be held anywhere along the shaft before aligning it to the hole in the board. Grasping the beads requires more precision due to the spherical structure. In addition to the different shapes of the pegs and beads, beads have to be held in a pattern such that the hole is not covered by the finger tips. The second factor that might contribute to the difference between the peg-board and bead-threading task is the precision level required for target placement. The requirement is high in the bead-threading task because the hole of the bead (0.5 cm) has to be aligned to the tip of the vertical needle. In case of the peg-board task, the peg has to be aligned to different holes' sizes (0.9 cm, 0.6 cm, 0.3 cm). In order to localize the holes of the board, less depth information is required since the board is located horizontally on the table. Determining the location of the needle requires more depth information, which might depend on ocular vergence. When binocular vision was removed, localizing the needle and aligning the hole of the beads to the needle was less accurate. In summary, removing binocular vision has different effects on manipulation tasks which could be due to the shape of the target, and the precision level of target placement.

2.4.3 Study limitations

The first limitation is that there was no measurement of the motor aspect of binocular vision (ocular vergence). Measuring the motor aspect of binocular vision might provide more insight and explain some of the variance in the binocular advantage. Furthermore, because this study was not conducted with a motion analysis system, the current data cannot be used to infer which stage of movement depend most on binocular vision. Lastly, due to fewer children who had stereoacuity ranging between the 50 and 70 seconds of arc, the interpretation of the explained variance for the binocular summation by stereoacuity should be applied with caution. A large sample size of children with higher stereoacuity threshold is required to confirm the results of this study.

2.4.4 Conclusions and future directions

The next step of this research is to quantify which component of the bead-threading task requires binocular vision using a motion analysis system. This step will be followed by testing children with abnormal binocular vision in the same age range (5-13 years) in order to investigate the significance of binocular vision in both tasks using the two outcome measures (i.e., movement time and the binocular summation). It is known that children with abnormal binocular vision perform worse than their peers (Birch, 2013; Goldstand, et al., 2005; Grant, et al., 2007; Grant et al., 2014; O’Connor, et al., 2003;, Suttle et al., 2010; Webber et al., 2008), but we do not know how much their performance will be affected. Because binocular summation can provide a more accurate estimate of the binocular advantage when compared to the movement time, such a measure needs to be quantified in children with abnormal binocular vision.

The findings of the present study provide important knowledge about the role of binocular vision in the performance of complex manipulation tasks in school-aged children. The tasks that we have chosen are used commonly to assess children’s fine motor skills; however, none of these tests have linked motor performance with binocular visual function. Thus, a major limitation of the current motor skills assessment batteries is that a low score identifies children with impairments, but it does not provide insight into why the deficit is present. Results from our study clearly show that performance of the bead-threading task is dependent on binocular vision, thus, deficits in performance on this task may be related to abnormal binocular vision. Children who are screened for movement disorders and score below age norms on the bead-threading task should be referred for an optometeric assessment after ruling out any cognitive or attentional disorders.

The current study also has implications for evaluating visuomotor skills in children with abnormal binocular vision due to amblyopia or strabismus, which occurs in 2-3% of otherwise typically developing children (AAO, 2012). Specifically, there may be a critical period for initiating treatments and some children may need highly specific visuomotor therapy in conjunction with vision therapy. In conclusion, this research has important implications for clinical decision-making about the choice of tasks used for assessment, as well as the development of optimal visuomotor therapies for children with abnormal binocular vision.

Chapter 3: Characterizing Performance of Fine Motor Skills in Children with Learning Difficulties

3.1 Literature review

Poor academic performance, a major concern for parents and educational specialists, can include difficulties in reading, comprehension, linguistic, and mathematical skills. When children require any form of assistance in order to complete school-related tasks, such as reading, writing, or mathematics, they are enrolled in a specific program administered by the Ontario School Board called Individualized Educational Plans (IEPs). Children included in these plans may have vision disorders. For example, studies have suggested that children with binocular vision dysfunctions are more likely to experience difficulties in reading, writing, and mathematics skills (Buzzelli, 1991; Goldstand, et al., 2005; Kirkby, Webster, Blythe, & Liversedge, 2008; Kulp & Schimdt, 1996; Quaid & Simpson, 2013; Palomo-Álvarez & Puell, 2010), as well as difficulties with performance of fine motor skills (Goldstand et al., 2005; Kulp, 1999; Luo, Jose, Huntsinger, & Pigott, 2007; Son & Meisels, 2006). The following literature review focuses on the relationship between binocular vision dysfunctions, academic performance (measured by reading, and mathematics abilities), and difficulties with performance of fine motor skills.

3.1.1 Association between binocular vision and learning difficulties

Binocular vision functions involve a cooperative work of both eyes and includes sensory and motor aspects: stereopsis and vergence, respectively. The sensory aspect of binocular vision can be assessed by determining the stereoacuity threshold and the fusional vergence, whereas measuring accommodation and vergence, namely amplitude of accommodation, accommodative facility, and vergence facility is used to assess the status of the motor aspect of binocular vision (Quaid & Simpson, 2013).

Stereopsis can be measured with different types of tests. For example, using real depth where stimuli are separated in depth naturally, or polaroid vectographs, where input to each eye is dissociated using glasses with different colored lenses or polarized lenses placed over each eye. A widely used clinical real depth tests is the Frisby stereotest which can be used at near and far distances. Polaroid vectograph tests can be further classified into tests that use contours or random dots. For example, the Titmus fly test uses contours, the Randot stereotest uses both contours and random dots, whereas the Randot Preschool stereotest uses random dots only. The agreement between the Frisby stereotest and Randot Preschool test at the near and far distances was assessed by Leske, Birch, and Holmes (2006). The tests were administered to 182 patients with strabismus ranging in age from 4 to 84 years, with 20/40 visual acuity or better in each eye. Results showed that patients attained lower stereoacuity thresholds (i.e., better depth perception) with near Frisby in comparison to the near Randot test. Similarly, 38% of patients attained measurable stereopsis with the distance Frisby test, but had no measureable stereopsis with the distance Randot test. Thus, random dot stereotests provide a more accurate measure of stereopsis compared to contour tests which contain monocular depth cues.

The agreement between the Randot test, the Randot Preschool test, and the Titmus test was also examined in children with known binocular vision disorders between 2.7 and 11.5 years (Fawcett & Birch, 2000). Results showed that the Randot test, the Randot Preschool test, and the Titmus test showed a good agreement in patients with thrresholds better than 100 seconds of arc. However, the Titmus test overestimated the stereoacuity threshold compared to the Randot Preschool test in 31% of patients with known binocular vision disorders due to strabismus. Similarly, patients with no measurable stereopsis on the Randot Preschool test were more likely to have 400 seconds of arc on the Titmus test, and 200 seconds of arc on the Randot stereotest. Overall, the choice of the method of stereoacuity threshold assessment depends on the purpose and the population who will be tested. For instance, the Randot Preschool test provides a better estimates of the stereoacuity threshold compared to the Titmus test in patients with known binocular vision abnormalities. In visually-normal children, the choice of the test is more flexible. Likewise, in the present study where children have suspected binocular vision dysfunctions, the Randot stereotest can be useful to determine the presence of stereopsis.

Considering the developmental aspect of stereoacuity, the range of stereoacuity in visually-normal preschool children (3-6 years) is 60-120 seconds of arc. Younger children are less able to achieve 60 seconds of arc (Afsari et al., 2013; Ciner et al., 2014). On average, 3-year-old children have a stereoacuity threshold of 100 seconds of arc, 5-year-old children had a stereaoacuity threshold of 60 seconds of arc, and 7-year-old children had a stereacuity threshold of 40 seconds of arc as measured by the Randot Preschool stereoacuity test (Birch et al., 2008). Stereopsis provides important information when making judgement about the objects' orientation and relative size in the near environment (McKee & Taylor, 2010). Improvement in the stereoacuity threshold may have an important implication for learning of fine motor skills during the childhood period.

The motor aspect of binocular vision, or motor fusion is the capability of both eyes to maintain alignment in order to achieve single binocular vision. The amount of vergence required before the occurrence of double vision is referred to as the fusional reserves (Weddell, 2013), which can be measured at near and at far distances. Fusional reserves are divided into divergent (negative fusional reserve) and convergent (positive fusional reserve) amplitude, which are measured with a base-in and a base-out prism bar, respectively. Convergence is required when fixation is changed from a farther object to a nearer object, and divergence is required when fixation is changed from a near object to a distant object. In the context of the school day, students require to change fixation by converging and diverging their eyes when copying from the board.

The status of accommodation and vergence, are measured by a series of tests such as amplitude of accommodation, accommodative facility, near point of convergence and vergence facility. The amplitude of accommodation is defined as the ability of the patient to focus on a near target (Elliot, 2007). The amplitude of accommodation is defined as the ability of the patient to focus on a near target (Elliot, 2007). The amplitude of accommodation can be also measured monocularly using minus lenses. The near point of convergence can be defined as the point where visual axes intersect when maximum convergence occurs and a single binocular vision is maintained (Elliot, 2007). Normative data for binocular visual functions in children and adults are reported in Table 3.1. Children’s norms for the divergent amplitude (Shiemann, &Wick, 2008) were much lower than adults (Morgan, 1944) suggesting that children needed a lower prism power to make the required divergent movement. On the other hand, children required a similar prism power to that of adults in order to achieve maximum convergence. Lastly, accommodative facility was significantly lower in children than in adults, suggesting a reduced ability of the accommodative system to overcome blur when negative lenses were placed in front of one eye during binocular or monocular viewing.

Table 3.1: Normative data for functions of binocular vision

Binocular vision function	**Normative data**
Stereopsis	Adults: 20-40 seconds of arc Children: <100 seconds of arc (Birch et al., 2008).
Divergent amplitude: Base-in break/ base-in recovery	21±4 PD/ 13±5 PD (Morgan, 1944). 12±5 PD/ 7±4 PD (Schieman, & Wick, 2008).
Convergent amplitude: Base-out break/ base-out recovery	21±6 PD/11±7 PD (Morgan, 1944). 23±8 PD/ 16±6 PD (Schieman, & Wick, 2008).
Accommodative facility	Children (8-12 years): Monocular: 7±2.5 cpm Binocular: 5±2.5 cpm Adults: Monocular: 11±5 cpm Binocular: 10±5cpm (Schieman, & Wick, 2008).
Amplitude of accommodation	The minimum amplitude of accommodation=15-0.25 x age. The average amplitude=18.5-0.3x age. The maximum amplitude=25-0.4x age (Elliot, 2007)
Vergence facility	15±3 cpm (Schieman, & Wick, 2008).

Table 3.2: Summary of research that examined the association between binocular vision and reading

Study Author/s	Test/s used	Number of participants	Results
Binocular vision and reading			
Buzzelli (1991)	Stereopsis, accommodative facility, vergence facility	13 typically-developing children (mean age 13 years and 3 months) 13 children with dyslexia (mean age 13 years and 4 months)	Fewer vergence movements as indicated by the vergence facility test (3.16 cpm in children with dyslexia compared to 5 cpm in normal children). All the other measures were not significantly different between the two groups.
Kulp & Schmidt (1996)	Reading performance and visual test: accommodative facility, stereoacuity using Randot stereotest, visual perceptual skills, near and distance visual acuity, and cover test for measuring phoria.	90 kindergarteners 91 first-graders	Accommodative facility was a significant predictor for reading performance in grade 1 children (p=0.02) and in the entire group (p=0.015).
Palomo-Álvarez &	Binocular functions: distance and near	87 poor readers,	Mean distance break and recovery were 2 diopters lower in children with reading

Puell (2010)	horizontal fusional vergence ranges, AC/A ratio, near point of convergence and sereoacuity	32 age-normal readers (age in both groups: 8- 13 years)	difficulties compared to children without reading difficulties (BI break=9.1±3.0 PD in poor readers; 11.1±3.4 PD in age-normal readers) (BI recovery =3.6±1.9 PD in poor readers; 5.0±2.4 PD in age-normal readers.
Quaid & Simpson (2013)	Academic performance was measured by the reading score, and eye movement while reading using Visagraph system III. Visual tests included: refractive error, vergence facility, vergence amplitudes, accommodative facility, accommodative amplitudes, fusional reserves, near point of convergence, and stereoacuity using Titmus stereotest.	50 typically-developing children (6-16 years) 50 children enrolled in IEPs (6-16 years)	Reduced vergence facility (7.31±3.37 cpm compared to 14.48±2.03 cpm in the control group), which was correlated with reading speed (ρ=-0.81), and the number of eye movement while reading (ρ=-0.79). Accommodative facility (monocular: IEP:8.24 cpm±3.58; control 12.81 cpm±1.57, binocular: IEP: 9.14 cpm±3.44; control: 13.52 cpm±1.6) accommodative amplitudes (IEP: 10.44 D±2.13; control: 12.86 D±1.3), near point of convergence (IEP: 10.76 cm±4.03; control: 7.48 cm±2.3), base-in break/recovery (IEP: 9.21 PD±4.37/7.02 PD±4.07, control: 13.28 PD±2.87/11.21 PD±2.59), base-out break/recovery at near (IEP: 15.88 PD±6.95/12.56 PD±6.2, control: 25.58 PD±5.67/21.05 PD±4.41), and stereopsis (IEP:65.2 seconds of arc±41.36; control: 32.4 second of arc±12.04) were significantly different between the two groups of children.
Visual perception and visual motor integration			
Goldstand,	1- Tests of visual efficiency: saccades, visual tracking,	46 proficient readers and	Visual efficiency tests were significantly poorer in non-proficient readers compared

Koslowe, & Parush (2005)	cover test at near and at far, near point of convergence, suppression using Worth 4-Dot, and stereoacuity. 2- Tests of visual health: distance and near visual acuity, retinoscopy, ophthalmoscopy, and color vision. 3-Visual perceptual abilities: The Motor-Free Visual-Perception Test. 4-Children's activities were evaluated by: The Revised Conners Parent and Teacher Rating Scale 5-Reading performance was assessed by The Altalef Reading Screening Test 6-Academic performance was assessed by The Academic Performance Questionnaire 7-Visual motor integration was assessed by The Developmental Test of Visual-Motor Integration.	25 non-proficient readers (12 year and 7 months).	to proficient ones (p=0.036). However, visual health was similar in the proficient and non-proficient readers (p=0.49). Children who did not have visual disorders have an overall better academic performance than those who have (p=.04). Children who have visual disorders performed worse than visually-normal children in visual perception test (p=0.05). However, both groups of children performed similar in visual motor integration tests (p=0.23).

The contribution of binocular vision to the performance of reading, writing, and mathematics skills has been addressed in the literature (Buzzelli, 1991; Goldstand et al., 2005; Kirkby, et al., 2008; Kulp & Schimdt, 1996; Quaid & Simpson, 2013; Palomo-Álvarez & Puell, 2010). Research that examined the relationship between measures of binocular vision, and academic performance is summarized in Table 3. 2. Factors reported to contribute to reading success are vergence facility (Buzzelli, 1991; Quaid & Simpson, 2013), accommodative facility (Kulp & Schimdt, 1996), distance fusional vergence (Palomo-Álvarez & Puell, 2010), and stereopsis (Goldstand et al., 2005; Kulp & Schimdt, 1996). Based on the research summarized above, a significant demand is placed on binocular vision during the performance of school-related work like reading, writing, copying from the board. For example, vergence and accommodation has to be maintained during reading (Quaid & Simpson, 2013). In summary, normal binocular vision functions is important for good academic performance.

Studies have shown that binocular visual function is associated with academic Performance . On the other hand, studies have also shown that performance of fine motor tasks is also associated with academic performance (Funk et al., 1986; Kulp, 1999; Luo et al., 2007; Stoeger et al., 2008; Schemidt & Perino, 1985). The association between fine motor skills and academic performance might be related to the implementation of certain math and spelling skills while manipulating small objects (Luo et al., 2007). For instance, sorting and counting are important mathematical skills which children apply during playing. They might sort and count the blocks based on shapes and colour while playing with building blocks. Furthermore, spelling and reading letters can be applied by children during playing with letter magnets. Overall, it seems that mathematical skills and reading are used when children engage in play activities.

Table 3.3: Summary of research that examined the association between academic performance and fine motor skills.

Study Author/s	**Test/s used**	**Number of participants**	**Results**
Motor skills and academic performance			
Funk, Sturner, Green (1986)	1-McCarthy Scales of Children's Abilities (MSCA) for assessment of cognitive and motor functions. 2-Vision, hearing, and speech screening were administered. 3-Reading and pre-reading skills were assessed the CTB/McGraw-Hill Prescriptive Reading Inventory (level 1) in kindergarten, during grades 1 and 2, the Prescriptive Reading Inventory	117 children tested initially and follow-up assessment was done during the kindergarten, grade 1 and 2 (totally, 110 in the kindergarten, 105 in the first-grade, and 92 in the second grade).	Scores of MSCA was correlated with the CAT reading scores in kindergarten (r=0.7), reading and math grade 1 (r=0.65, 0.56), and grade 2 (r=0.66, 0.53). Of the verbal (r=0.43, r=0.38), motor (r=0.32, 0.27), memory (r=0.48, r=0.53), and quantitative (r=0.53, r=0.51), the Perceptual-Performance scale was the strongest predictor of later achievement in reading (r=0.6) and math (r=0.5).

	(levels 2 and A) 3-the Diagnostic Mathematics Inventory (levels A and B) were used to correlate with scores of California Achievement Test (CAT) reading and mathematics scale scores		
Kulp (1999)	1-Berry Developmental test of Visual Motor Integration involves copying shapes of varying degrees of complexity. 2-Children's' academic performance were assessed by teachers' rating for children in reading, math, writing, and spelling. 3-Stanford Diagnostic Reading Test was used to assess reading skills in Grade 1. 4-Ottis Lennon School Ability was used to assess school-cognitive ability in Grade 2.	191 children between 5-9 years.	A significant association between the performance on the visumotor test and achievement in reading in 7-(r=0.53, p<0.0001), 8-(r=0.42, p=0.002), and 9-(r=0.315, p=0.0517), but not in the 5-and 6- years old (r=0.16, p=0.25), math in 7-(r=0.55, p<0.0001), 8-(r=0.4, p=0.004), and 9-(r=0.5, p=0.03), but not in the 5-and 6- years old (r=0.17, p=0.2), writing in 7-(r=0.6, p<0.0001), 8-(r=0.37, p=0.008), and 9-(r=0.398, p=0.016), but not in the 5-and 6- years old (r=0.05, p=0.7), and spelling in 7-(r=0.53, p=0.05), 8- (r=0.298, p=0.04), and 9-years old(r=0.44, p=0.007).

Luo, Jose, Huntsing, & Pigott (2007)	Children's math skills: number sense, number properties and operations, measurement, geometry and spatial sense, and patterns. Fine motor skills assessed in the first part of kindergarten year: The Early Screening Inventory-Revised involving three tasks: gate replication, shape copying, and drawing a person without a model.	244 East Asian American (mean age=5.6 years) and 9,816 European American children (mean age=5.72 years).	Performance of fine motor skills namely shape copying, and drawing a person predicted mathematics skills for children in the kindergarten and grade 1. One point improvement in the scores of fine motor test resulted in 1.68 improvement in the math score.
Schemidt & Perino, (1985)	Scores of The Vane Test of Language and The Vane Kindergarten Test were compared to the Metropolitan Achievement Test scores in reading and math, The Otis-Lennon School Ability Test index. VKT is an intelligence test administered in the beginning of kindergarten, measures intelligence using vocabulary, drawing a man, visuo-motor copying tasks. VTL measure both expressive and receptive language skills.	378 students were followed from the beginning of the kindergarten through grade 2	Performance on the entry test (VKT) predicted 77 % of children who were enrolled in special education classes and 73% of children with high academic achievement.

Stoeger, Ziegler, &Martzog (2008)	Cognitive abilities were assessed by Culture Fair Intelligence test. Fine motor skills: draw a curved line between two parallel lines about 4mm apart from one another as quickly as possible without crossing the borders. Concentration was evaluated by “Aufmerksamkeits-Belastungs-Test” d2 where children marked the target stimulus among distractors as fast as possible.	128 gifted students identified, 31 were found to be underachievers, 97 achievers.	Performance of fine motor skills was significantly worse in the underachievers compared to the achievers. Specifically, underachievers made more contacts when drawing a curved line between two parallel line (12.23±7.14) compared to the achievers (8.43±7.98). (t (126) = 2.36, $p < 0.05$). The total score of the performance of fine motor skills and the interaction between fine motor skills and the errors on the concentration test were significant predictors explained 12% of the variance.

3.1.2 Relationship between binocular vision and fine motor skills

Our findings from study 1 suggest that the contribution of binocular vision to task performance is greater in the bead-threading task than in the peg-board task in children between 5-12 years. Binocular advantage was defined as the extent of improvement in task performance during binocular viewing compared to monocular viewing. Results from study 1 indicated that a binocular advantage was evident in all groups of children (young, middle, and older groups) as well as the adults group during the performance of the bead-threading task. In contrast tothe bead-threading task, binocular advantage was significantly lower in the peg-board task. Importantly, the development of stereoacuity was associated with the improvement in performance of the bead-threading task. The findings from study 1 were based on healthy children with no visual, cognitive or developmental problems. After determining the extent of binocular advantage in both tasks in visually-normal children, the next step of this research was to compare the performance of children with and without learning difficulties on both tasks. Children enrolled in the Individualized Educational Plans were identified by their teachers as having reading difficulties. As summarized in the literature review, an association between functions of binocular vision and reading facility was made by several researchers (Buzzelli, 1991; Goldstand et al., 2005; Kirkby, et al., 2008; Kulp & Schimdt, 1996; Quaid & Simpson, 2013; Palomo-Álvarez & Puell, 2010). Furthermore, the association between academic performance and the performance of fine motor skill has also been examined in other studies (Funk et al., 1986; Kulp, 1999; Luo et al., 2007; Stoeger et al., 2008; Schemidt & Perino, 1985).

Children who performed poorly in school were more likely to perform poorly on manipulation skills. Thus, an important question is what the relationship between binocular vision, academic performance, and the performance of fine motor skills? If children with learning difficulties have abnormal binocular vision as well as difficulties in the performance of fine motor skills, healthy binocular vision may be required for development of both cognitive functions and fine motor skills.

3.1.3 Research objectives and questions

The first objective of this study was to examine performance on the bead-threading and peg-board tasks in children with learning difficulties (i.e., those enrolled in the IEP) and to compare their performance to that of children without learning difficulties. The second objective was to examine the association between measures of binocular visual functions and the performance of fine motor tasks. This research aimed to answer two questions:

1. What is the difference in the performance of the bead-threading and the peg-board tasks between children with and without learning difficulties?
2. What is the association between binocular vision and poor performance of fine motor skills?

3.1.4 Hypotheses

1. Children with learning difficulties will have significantly longer movement times in comparison to children in the control group during both viewing conditions in both tasks.

2. Binocular visual functions will be associated with the performance on the bead-threading task. Specifically, movement time will be longer in children with lower accommodative facility, lower convergence and divergence amplitudes

3.2 Method

3.2.1 Participants

Twenty-one children with learning difficulties (i.e., those who enrolled in the IEP) were recruited. Children were identified by their teachers as having difficulties with reading and writing. Two children were excluded because one of them had amblyopia and the other one had cyclopentolate 1% ophthalmic solution eye drops that blurred vision. In order to compare motor performance of children with learning difficulties (IEP group) to that of children without learning difficulties (control group), children with IEP were matched for age and gender as close as possible with the children who participated in study 1.The number of participants, gender distribution, and stereoacuity range are reported in Table 3.4.

Children in the IEP group underwent a detailed binocular vision assessment namely visual acuity, stereopsis, fusional reserve at near and at far, binocular and monocular accommodative facility, amplitude of accommodation, and near point of convergence. The binocular vision assessment was conducted by third-year students at the School of Optometry and Vision Science under the supervision of a licensed optometrist.

Table 3.4: Number of participants, gender distribution, and stereoacuity range in the control group and the IEP group

	Young control group	**Young IEP group**	**Middle control group**	**Middle IEP group**	**Older Control**	**Older IEP group**
N (sample size)	4	4	8	8	7	7
Gender	3 girls	2 girls	5 girls	3 girls	5 girls	3 girls
Stereoacuity (seconds of arc)	20-40	20-25	20-70	20-50	20-30	20-50

3.2.2 Experimental procedure

Peg-board and bead-threading tasks were used following the same procedure that was used in section 2.2.2 of this thesis.

3.2.3 Analysis

The first objective of this research was to compare the performance on the bead-threading and peg-board tasks between children in the IEP and the control groups. This was examined using a mixed model analysis of variance (ANOVA) using both movement time and the binocular summation as the dependent variables. The data of the young groups was removed from the ANOVA analysis due to a small-sample size; however, their data is plotted in the figures. The between-subject factors were Age (middle, older), and Group (control, IEP). The two within-subject factors were Viewing Condition (binocular, monocular) and Target Size (small, large for the bead-threading task, and small, medium, large for the peg-board task). The dependent variable for this analysis was movement time. ANOVA was performed for each ask separately. The control and the IEP groups were compared using the binocular summation as outcome variable. The between-subject factors were Age (middle, older), and Group (control, IEP). The two within-subjects factors were Task (bead-threading, peg-board) and Target Size (small, large). Significant main effects and interactions were investigated using Tukey-Kramer post-hoc test with alpha-level of 0.05

The second objective was to examine the association between binocular visual functions and movement time in the bead-threading and the peg-board tasks. Pearson correlation was conducted between movement times in each viewing condition in both bead-threading, and peg-board tasks and functions of binocular vision, namely amplitude of accommodation, accommodative facility, base-in break/recovery, and base-out break/recovery.

3.3 Results

3.3.1 Effect of learning difficulties on movement time

3.3.1.1 Bead-threading task

The first aim of this research was to compare the performance of the bead-threading and the peg-board tasks between children with and without learning difficulties. The results from the statistical analysis showed a significant effect of Group, Age, Viewing Condition and Target Size (see Table 3.5 for a description of all statistical effects). The mean movement time during binocular and monocular viewing in the control and the IEP groups is plotted in Figure 3.1A. Children in the IEP group had a longer movement time compared to children in the control group, and children in the middle group were slower than children in the older group. As expected, all children were slower during monocular compared to binocular viewing. Children in the IEP group had significantly longer movement times compared to the control group in both viewing conditions. In addition, there was a significant interaction between Group and Viewing Condition ($F_{1,27}=4.55$, $p=0.042$). As shown in Figure 3.1A, mean movement time of children in the IEP group during binocular viewing was comparable to the mean movement time of the control group during monocular viewing. Furthermore, the difference between viewing conditions was greater in the IEP groups (middle: 14.05±15.3 s; older: 15.00±10.5 s), compared to the control (middle: 11.79±6.44 s; older: 6.45±3.41 s), suggesting a greater effect of removing binocular vision in the IEP group compared to the control group. These results indicate that children in the IEP group have a greater difficulty performing a fine motor task in both viewing conditions; however, they are affected relatively more by the removal of binocular vision.

3.1.1.2 Peg-board task

Results from the statistical analysis are reported in Table 3.5. In contrast to the bead-threading task, children in the IEP group had a similar movement time to children in the control group when performing the peg-board task during binocular and monocular viewing, respectively (middle control: 22.25 s ±5.25, 25.51s ±5.802; middle IEP: 21.50 s±4.27, 25.56 s±5.88; older control: 18.49 s ±4.12, 20.84 s ±3.66; older IEP: 20.37 s ±3.81, 21.92 s±3.57). There was also no significant interaction between Group and Viewing Condition for the peg-board task. Overall, children in the IEP and control groups had similar performance during binocular and monocular viewing for both peg sizes in the peg-board task.

Table 3.5: Statistical models for the main effects and the interaction effects for the bead-threading and the peg-board tasks.

	Bead-threading task	**Peg-board task**
Age	$F_{1,27}$=4.76, p=0.038	$F_{1,25}$=8.17, p=0.0085
Group	$F_{1,27}$=31.19, p<0.0001	$F_{1,25}$=0.33, p=0.57
Viewing	$F_{1,27}$=65.27, p<0.0001	$F_{1,25}$=33.79, p<0.0001
Target size	$F_{1,27}$=11.19, p=0.0019	$F_{1,25}$=60.18, p=0.0004
Group*Viewing	$F_{1,27}$=4.5, p=0.04	$F_{1,25}$=0.03, p=0.87

Age*Viewing	$F_{1,27}$=13.62, p=0.398	$F_{1,25}$=1.83, p=0.19
Group*Target size	$F_{1,27}$=1.74, p=0.198	$F_{1,25}$=0.23, p=0.64
Age*Target size	$F_{1,27}$=1.77, p=0.195	$F_{1,25}$=2.34, p=0.14

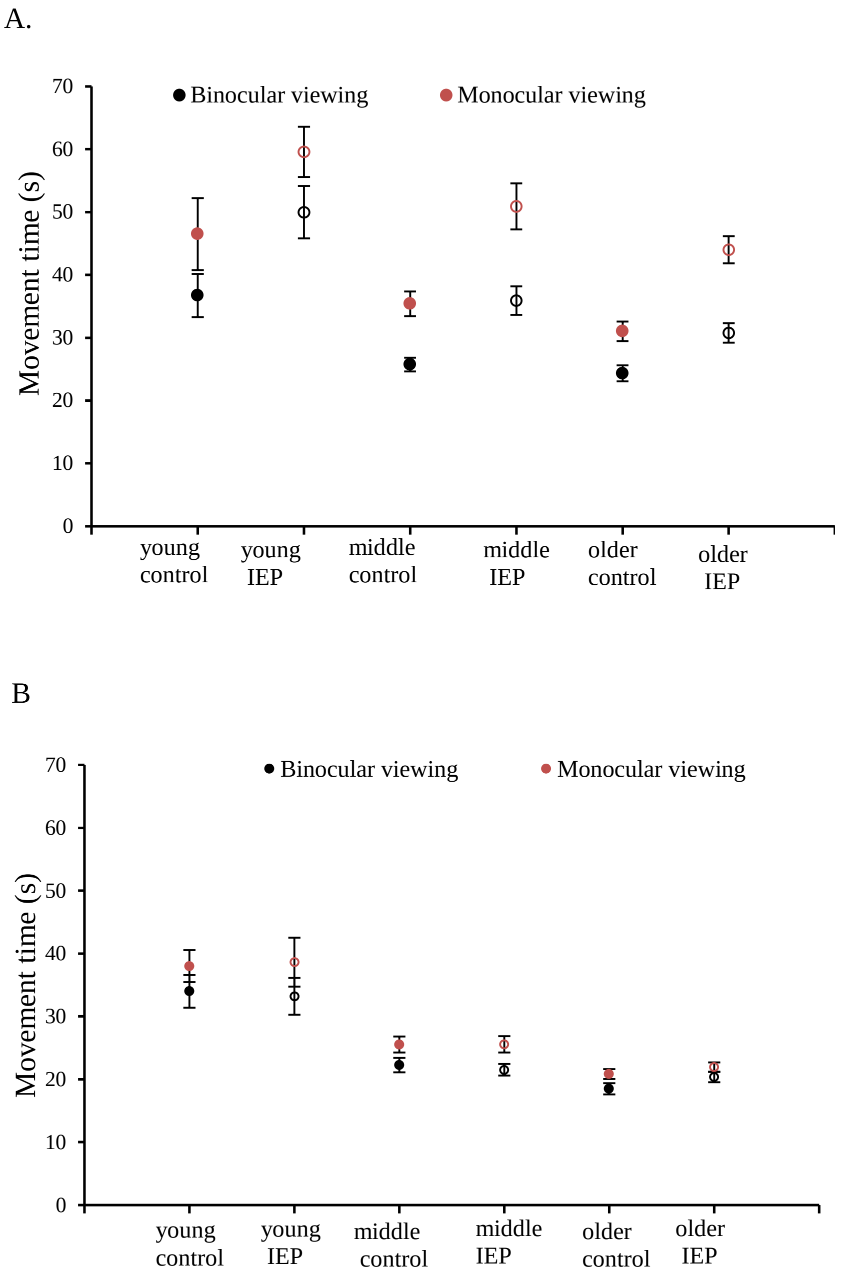


Figure 3.1: Mean movement time plotted for the control and the IEP groups during binocular and monocular viewing in the (A) bead-threading task, and (B) peg-board task.

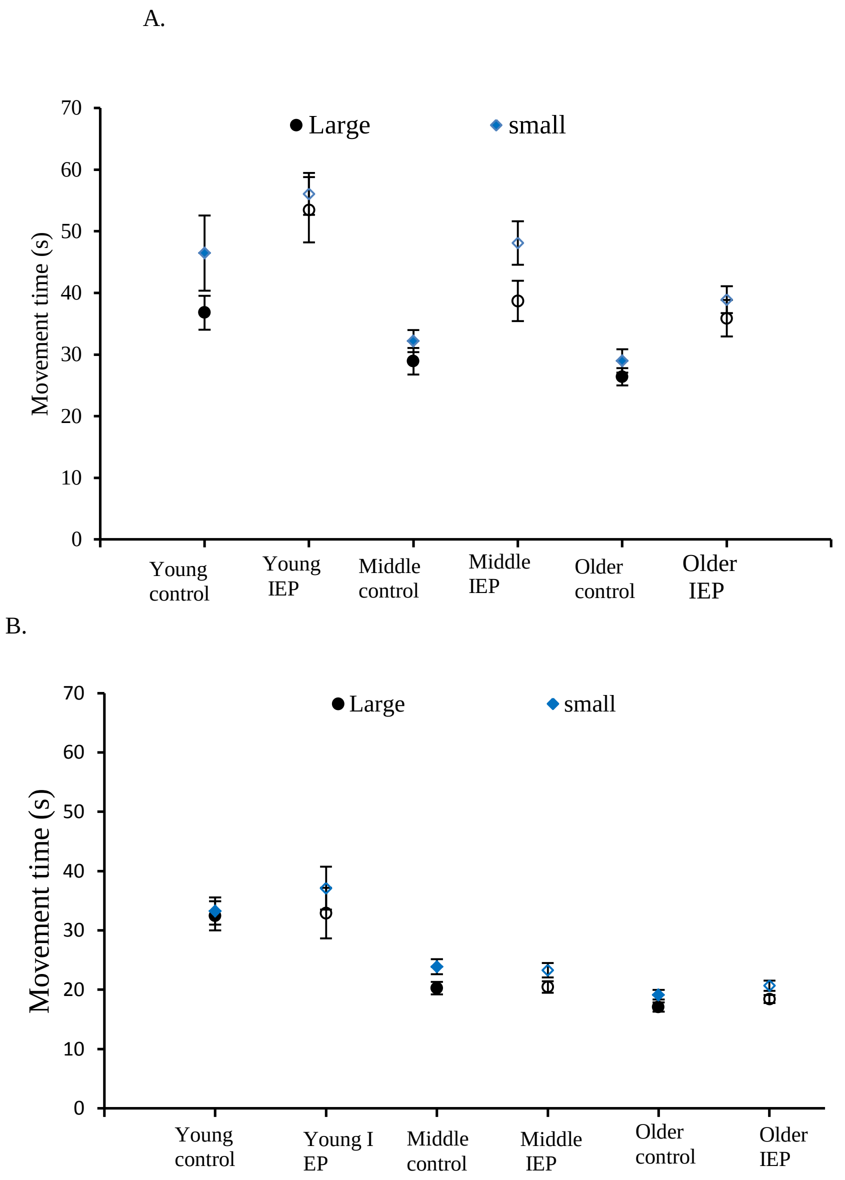


Figure 3.2: Mean movement time plotted for the Control and the IEP groups for the large and small targets in the (A) bead-threading task, and (B) peg-board task.

3.3.2 The effect of learning difficulties on the binocular advantage

The comparison between the control and the IEP groups was also performed for the binocular summation to examine the extent of binocular advantage in each group. Results from the ANOVA showed no significant effect of Age ($F_{1,27}$=0.20, p=0.66), Group ($F_{1,27}$=0.10, p=0.76), Target Size ($F_{1,56}$=0.37, p=0.55), and interaction between Group and Task was not significant ($F_{1,26}$=1.16, p=0.29). A significant main effect of Task was found ($F_{1,26}$=39.76, p<0.0001), suggesting that the mean binocular summation in the bead-threading task (0.76) was lower than in the peg-board task (0.89) as shown in Figure 3.3. Overall, children with learning difficulties have a binocular advantage similar to their age-matched control, which is lower in the bead-threading task than in the peg-board task.

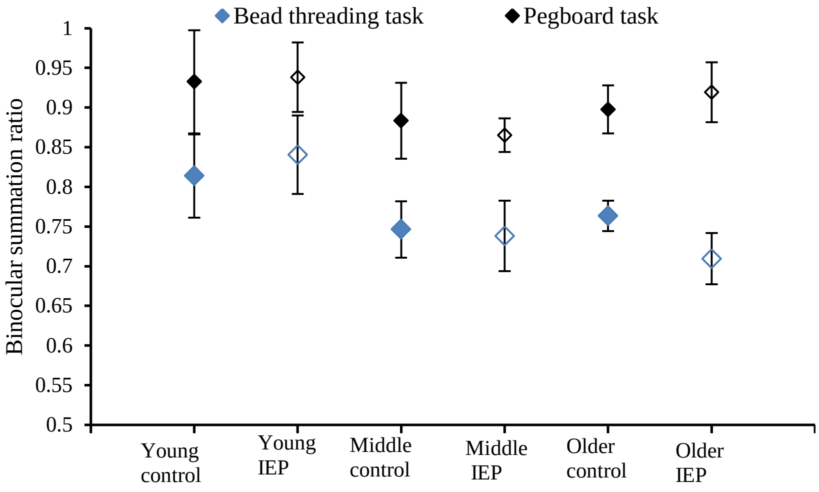


Figure 3.3: Mean binocular summation ratio in the control and IEP groups in both bead-threading and peg-board tasks.

3.3.3 The association between binocular vision and movement time

The second objective of this research was to examine the association between aspects of binocular vision and performance of fine motor skills as examined by movement time, and/or the binocular summation. Because there was no significant difference between the control and the IEP groups for the peg-board task, correlation between measures of binocular function and movement time in the peg-board task was not examined. Furthermore, the peg-board task was less sensitive to binocular vision because the effect of viewing was greater in the bead-threading task than in the peg-board task as confirmed by the binocular summation.

Before examining the relationship between functions of binocular vision and movement time in the bead-threading task, children's data was compared to the published children's norms (Elliot, 2006; Morgan, 1944; Sheimann & Wick, 2008, see Table 3.1). The negative fusional reserves (i.e., both the break and the recovery points) were not significantly different from the average norms of children ($p=0.63$, $p=0.14$) as shown in Figures 3.4A and 3.4B, respectively.

The positive fusional reserve (i.e., both the break and the recovery points) in children were significantly lower than the average norms of children ($p<0.0001$, $p=0.002$), respectively as shown in Figures 3.5A and 3.5B.

The average binocular accommodative facility in the IEP group was higher than the published norms ($p=0.008$), and monocular accommodative facility was not significantly different from the average norms ($p=0.13$) as shown in Figures 3.6A and 3.6B, respectively.

The amplitude of accommodation was compared to the average age-based norms, (the average amplitude of accommodation=18.5- 0.3 x age). Because no significant difference was found between left-eye and right-eye amplitude of accommodation ($p=0.96$), the average amplitude of accommodation was used for further analysis. The average monocular amplitude was significantly lower than the average age-based norms (p=0.001) as shown in Figure 3.6C.

Results of the correlation metrics between the measures of binocular vision and movement time during binocular and monocular viewing are reported in Table 3.7. A significant negative correlation was found between monocular accommodative facility and movement time during monocular viewing (r=-0.75). Furthermore, a significant negative correlation was found between binocular accommodative facility and movement time during monocular viewing (r=-0.88). Lastly, the amplitude of accommodation was negatively correlated with movement time during binocular viewing (r=-0.88). Even though the correlation between the divergence and the convergence amplitude measured by base-in and base-out prism bar was not significant, the association was always negative. In order to provide the size of the association between accommodation and movement time in the bead-threading task, stepwise regression analysis was conducted with movement time during binocular and monocular viewing as dependent variables and with amplitude of accommodation, binocular, monocular accommodative facility, base-in break and recovery, base-out break and recovery points, and stereoacuity as the explanatory variables. Results showed that the amplitude of accommodation explained 61% of the variance (β=-1.68, p=0.02) during binocular viewing. Monocular accommodative facility explained 53% of the variance (β=-2.23, p=0.04), and stereoacuity explained 5% of the variance (β=-0.47, p=0.06) in movement time during monocular viewing. In summary, the ability of the accommodation system seems to be important during the performance of the bead-threading task.

Table 3.6: Description of the measures of binocular vision in children with learning difficulties.

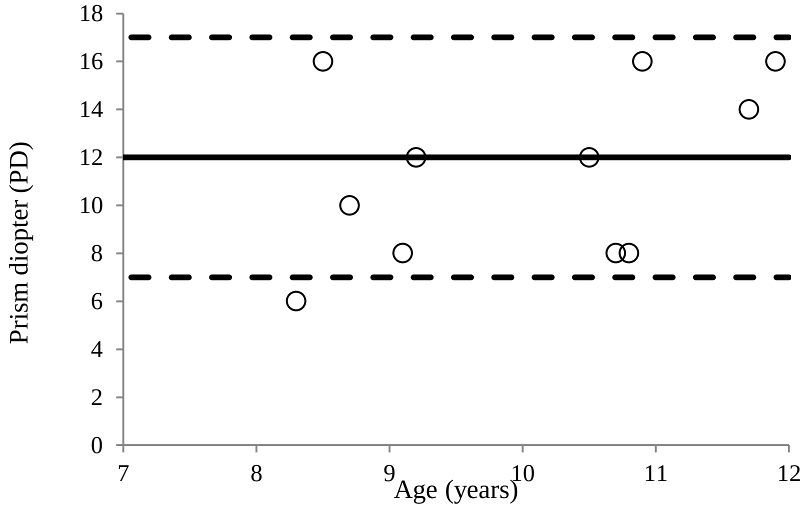
The measured function	**Sample size**	**Mean (standard deviation)**
Base-in break/recovery	11	11.45 PD(3.7)/8.91 PD(4.04)
Base-out break/recovery	11	11.45 PD(3.7)/8.91 PD(4.04)
Monocular accommodative facility	9	8.58 cpm (2.84)
Binocular accommodative facility	9	8.44 cpm (2.98)
Amplitude of accommodation	11	12.8 PD (2.14)

Table 3.7: The correlation metrics between measures of binocular vision and movement time during binocular and monocular viewing presented as Pearson's correlation parameter r (p-value). The asterisk represents a significant correlation at an alpha-level of 0.05 N=8.

	Movement time during binocular viewing (large beads)	Movement time during binocular viewing (small beads)	Movement time during monocular viewing (large beads)	Movement time during monocular viewing (small beads)
Stereoacuity	-0.4 (0.33)	-0.2 (0.6)	-0.3 (0.47)	-0.54 (0.16)
Amplitude of accommodation	-0.88 (0.004)*	-0.78 (0.02)*	-0.6 (0.12)	-0.47 (0.24)
Monocular	-0.57 (0.14)	-0.2 (0.63)	-0.75 (0.03)*	-0.73 (0.04)*

accommodative facility				
Binocular accommodative facility	-0.43 (0.29)	-0.26 (0.52)	-0.88 (0.004)*	-0.59 (0.12)
Base-in break	-0.43 (0.28)	-0.37 (0.36)	-0.56 (0.14)	-0.67 (0.07)
Base-in recovery	-0.52 (0.19)	-0.5 (0.2)	-0.46 (0.25)	-0.5 (0.16)
Base-out break	-0.43 (0.28)	-0.37 (0.36)	-0.56 (0.14)	-0.67 (0.07)
Base-out recovery	-0.52 (0.19)	-0.5 (0.2)	-0.46 (0.25)	-0.5 (0.16)

A.



B.

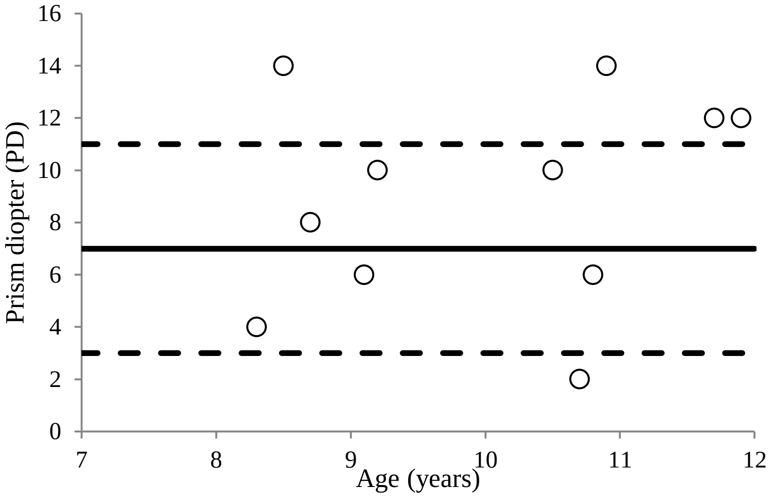
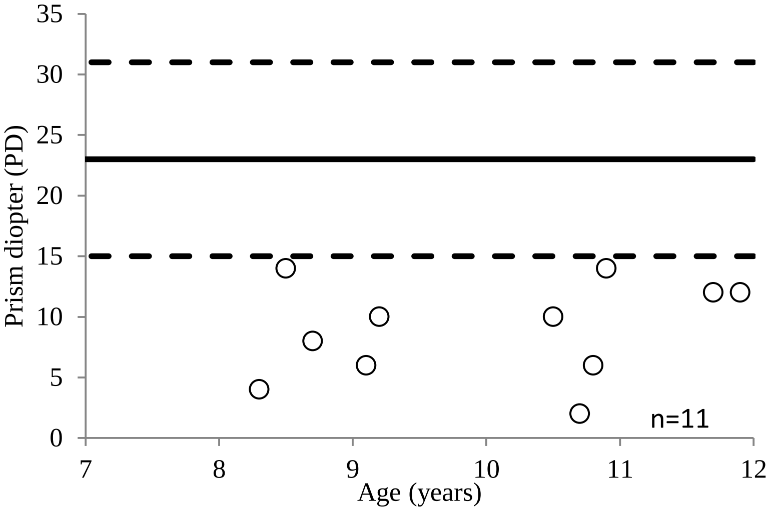


Figure 3.4: The relationship between children's in the IEP data and adults' norms for (A) the break point (B) the recovery point of the divergence amplitude (negative fusional vergence).

A.



B.

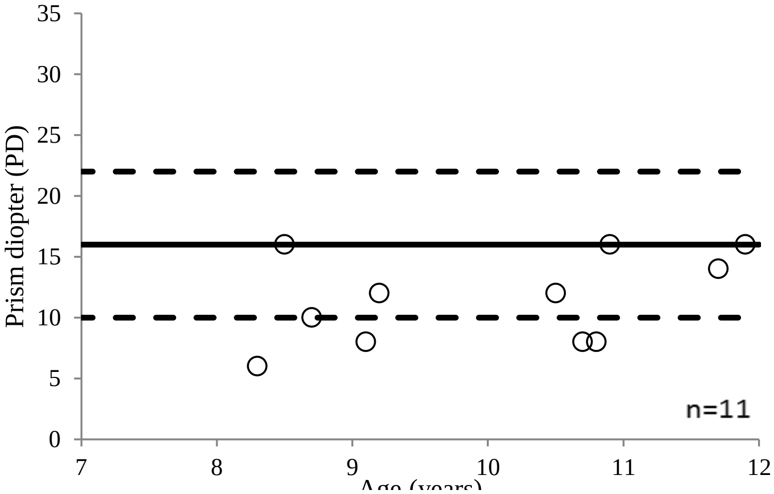
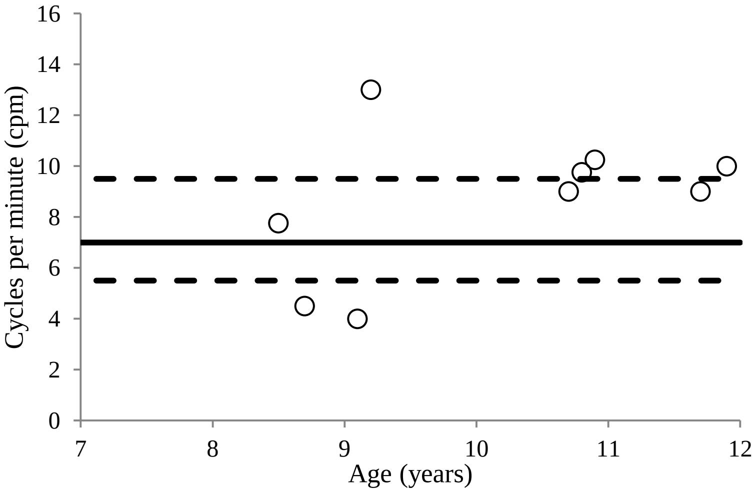


Figure 3.5: the relationship between children's data in the IEP group and children's norms for (A) the break point (B) the recovery point of the convergence amplitude (Positive fusional vergence).

A.



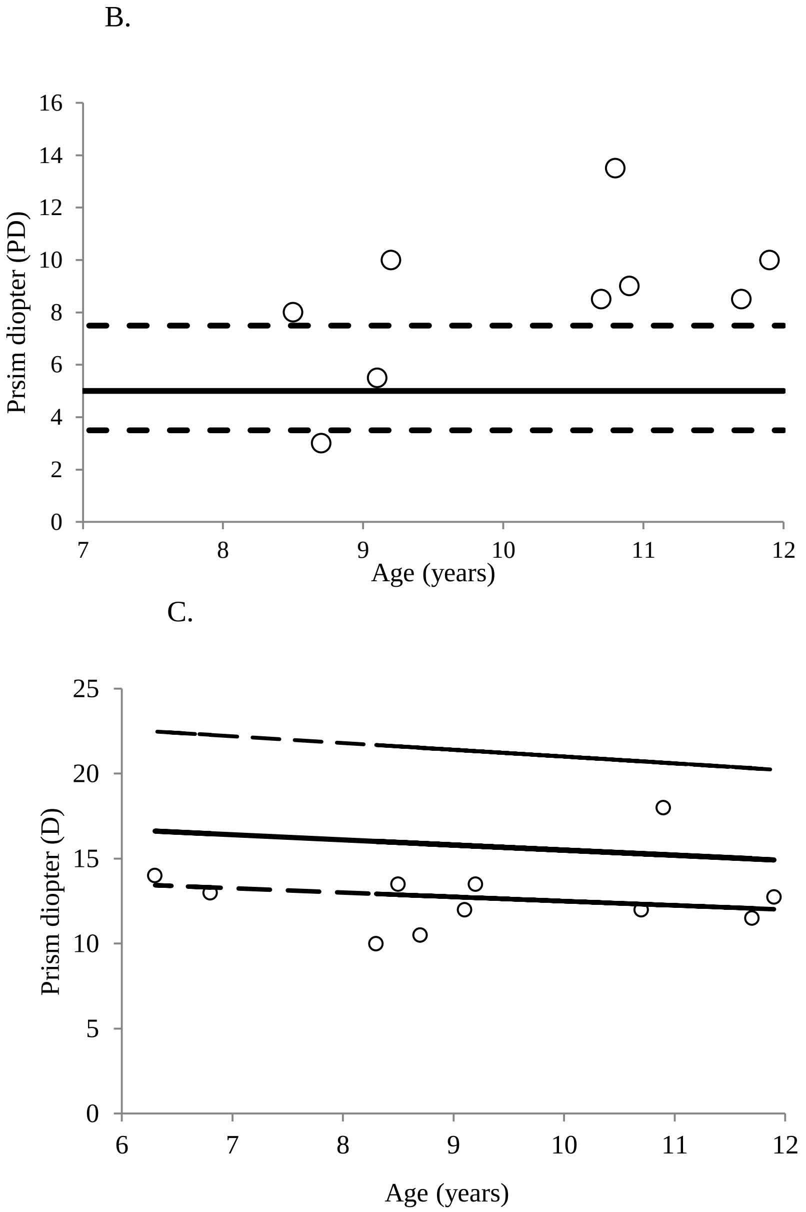


Figure 3.6: The relationship between children’s data and published norms for a. binocular accommodative facility, b. monocular accommodative facility, and c. amplitude of accommodation. The minimum amplitude of accommodation=15-0.25 x age, the average amplitude=18.5-0.3x age, and the maximum amplitude=25-0.4x age

3.4 Discussion

3.4.1 The effect of learning difficulties on the performance of fine motor skills

The aim of the current study was to examine the performance of fine motor skills in children with learning difficulties. Our results are in agreement with previous studies which found that the performance of fine motor skills distinguishes between children with and without learning difficulties (Funk et al., 1986; Kulp, 1999; Luo, et al., 2007; Stoeger et al., 2008; Schemidt & Perino, 1985). The results of the present study showed that children with learning difficulties in both age groups required more time to complete the bead-threading task in both viewing conditions. In fact, their movement time during binocular viewing was comparable to the movement time obtained in the monocular viewing by children in the control group. Notably, the significant interaction between group and viewing condition in the bead-threading task indicates that children with learning difficulties were more affected by the removal of binocular vision. It was expected that children with learning difficulties would have a lower binocular summation in comparison to children in the control group. However, statistical analysis showed that the binocular summation was comparable between the two groups of children in the middle and older groups. This indicates that children with learning difficulties had a similar *relative* binocular advantage for the performance of the bead-threading task. In contrast to the bead-threading task, the difference between the two groups of children was not present for the performance of the peg-board task. This is an important finding because it suggests that motivation was not the main reason contributing to the effect obtained in the bead-threading task. If children with learning difficulties lacked the motivation to perform the experimental tasks to the best of their ability, we would expect similar decrement in the performance of both tasks. However, children with learning difficulties were as fast as their peers in the control group during the performance of the peg-board task.

Surprisingly, a similar relative binocular advantage was found in the two groups of children. This was due to the fact that children with learning difficulties were slower during both, binocular and monocular viewing conditions, compared to their peers in the control groups. It is possible that the binocular advantage is similar in children regardless of their learning abilities. We have found in study 1 that binocular advantage was evident in all children, regardless of age, and it was less than that of adults. This finding indicates that children of any age between 5 and 12 years benefit from the availability of binocular vision during the performance of fine motor skills. Due to the simple requirement of the peg-board task, it failed to show any difference in motor performance between children with learning difficulties and their peers in the control group. Overall, the performance on complex manipulation tasks could be a useful tool to differentiate between children with and without learning difficulties.

The significant difference between the two groups of children could be linked to the fact that children with reading difficulties have a general learning difficulty or a binocular vision disorder. It is possible that children in the IEP group require a longer time to learn how to perform a given task or to solve a given problem. The bead-threading task requires a high level of hand-eye coordination, which requires the ability to process sensory feedback quickly during planning and execution of sequential movements. This task places a great demand on the visual system, and particularly on binocular vision.

3.4.2 The association between binocular visual functions and the performance of fine motor skills

Previous research found an association between reduced aspects of binocular vision and reading difficulties (Buzzelli, 1991; Goldstand et al., 2005; Kulp & Schimdt, 1996; Palomo-Álvarez & Puell, 2010; Quaid & Simpson, 2013). Moreover, other studies reported that difficulties in the performance of fine motor skills were associated with reading and math difficulties (Funk et al., 1986; Kulp, 1999; Luo et al., 2007; Stoeger et al., 2008; Schemidt & Perino, 1985). Our aim was to explore if a connection can be made between binocular vision, learning difficulties, and the performance of fine motor skills. Even though the results of the present study cannot provide a definitive conclusion, they help to draw an association between binocular vision, the performance of fine motor skills and reading difficulties.

Because some children could not understand the concept of some tests used to asses binocular visual function, only half of the children in this study succeeded in completing the binocular vision assessment. Children in the IEP group had a divergence range that was similar to that of the published age norms. However, the convergence range, both break and recovery points, was significantly lower in comparison to the published norms (Schiemann & Wick, 2008). In other words children in the IEP group had lower convergence abilities because their ability to maintain single vision was disrupted with a lower prism power. Although the correlation between measures of vergence range and movement time during the performance of the bead-threading task was not significant, this may be due to a lack of power because the sample size was small.

The binocular accommodative facility of children in the IEP group was similar to that of the published norms of children (Schiemann & Wick, 2008). However, these children had a lower monocular accommodative facility and amplitude of accommodation in comparison to age-based norms. The reason for normal binocular accommodative facility could be due to the contribution of vergence during binocular viewing. Therefore, when the vergence component was removed during monocular viewing, children with learning difficulties had poorer responses. The negative correlation between measures of accommodation and movement time suggests that poor accommodation response results in longer movement time to complete the bead-threading task. The results from a regression analysis showed that a reduction in the amplitude of accommodation by one diopter was associated with 1.15-seconds increase in movement time on the bead-threading task during binocular viewing. Additionally, a reduction in monocular accommodative facility by one cycle was associated with a 2-seconds increase in movement time during monocular viewing. These results are in agreement with Rafique & Northway (2015) who found that children with a Developmental Coordination Disorder (DCD) had reduced accommodation which was correlated with poor performance of fine motor skills assessed by the Bruininks–Oseretsky Test of Motor Proficiency (BOTMP).

Results from the present study provide preliminary support for the hypothesis that disruption of binocular visual functions is associated with impaired performance of fine motor skills in children with learning difficulties. The demand on both the convergence and the accommodation system is very significant in the bead-threading task, particularly when aligning the hole of the bead to the needle. The data reported in this study support that healthy binocular vision (i.e., stereoacuity, vergence, and accommodation) has an important role in the development of fine motor skills. Specifically, these data draw a possible link between vergence, accommodation, learning difficulties and the performance of complex manipulation tasks. Overall, the presence of binocular vision disorders and learning difficulties might both contribute to the difficulties in the performance of fine motor skills.

3.4.3 Study limitations

The limitations of the present study are that the results were based only on 20 children with learning difficulties. Due to the small sample size, the analysis of the behavioral data may lack statistical power. Furthermore, there was no complete data from the binocular vision assessment for all children. Due to their learning difficulties, half of the children could not understand the concepts of the tests, and thus no measureable responses were provided. Thus, caution should be used with generalization of the results as the findings might not be an accurate representation of the general population of children with learning difficulties. Lastly, a complete binocular vision assessment was not conducted on the control group of children, only their visual acuity and stereoacutiy were assessed. These measures were within the age-normal range and we assumed that they had normal vergence and accommodation functions as they did not report any symptoms of visual deficits. Future studies need to assess both accommodation and vergence when examining the performance of complex manipulation tasks in children without learning difficulties.

3.4.4 Conclusions

This study set out to determine the effect of learning difficulties on the performance of the bead-threading and the peg-board tasks. Additionally, we aimed to draw an association between binocular vision, fine motor skills and learning difficulties. This study has shown that children with learning difficulties performed worse than their age-matched peers on the bead-threading task, but had similar performance on the peg-board task. This study further confirms the findings from study 1 about the sensitivity of the bead-threading task over the peg-board task to the removal of binocular vision. Because children with learning difficulties were slow in both viewing conditions, the binocular summation was similar to that of age-matched peers. Despite its exploratory nature, this study offers some insight into a possible association between motor aspects of binocular vision, learning difficulties and the performance of fine motor skills. The results of this pilot work on children with learning difficulties suggest that healthy binocular vision during childhood might provide an important input for the development and learning of fine motor skills, reading and writing abilities. The results of the present study suggest the need for including assessment of binocular vision namely stereoacuity, vergence, and accommodation as well as fine motor skills in children with learning difficulties.

Chapter 4:

Study 3: Binocular Advantage during Tool-use in Healthy Adults

4.1 Literature review

Binocular advantage is defined as the improvement in task performance during binocular viewing compared to monocular viewing (Howard, 2000). Having two frontally placed eyes with overlapping visual fields provides two important advantages: binocular summation and binocular disparity. When inputs from both eyes contain correlated stimulus signals they summate during visual processing, whereas the noise signals in the stimulus from each eye are uncorrelated, effectively cancelling each other when combined. As a result, the signal-to-noise ratio in the stimulus signals increases during binocular viewing, which, in turn, leads to more reliable sensory information (Jones & Lee, 1981). Previous psychophysical studies have shown that binocular summation is a mechanism that improves visual acuity, contrast sensitivity, and detection of camouflaged objects (Banton & Levi, 1991; Baker et al., 2007; Jones & Lee, 1981).

The horizontal separation between the two eyes gives rise to disparate images in both eyes and is the bases of stereopsis, which provides an unparalleled resolution of relative depth and object structure/shape (Howard, 2002). Several studies that examined the contribution of binocular disparity to object recognition and scene processing showed reduced errors and shorter reaction time when objects were presented stereoscopically rather than on a flat, two-dimensional (2D) surface. In addition, this advantage was significantly greater when subjects were asked to recognize objects presented from a different viewpoint.

One of the first studies to examine the binocular advantage during a variety of perceptual and motor tasks was conducted by Jones and Lee (1981). They found 30% to 64%, improvement in the performance of perceptual tasks, such as letter identification, detection of a camouflaged object, and color discrimination. Additionally, more accurate and faster performance was found during performance of motor tasks such as threading beads (i.e., movement time was reduced during binocular viewing by 85%), tracking a moving target (i.e. performance was worse during monocular viewing by 78%), and water pouring (less spilling during binocular viewing by 22%). The binocular advantage found in perceptual tasks was most likely due to binocular summation. On the other hand, binocular disparity and ocular vergence provide important sensory information about relative and absolute depth which is essential during the performance of visuomotor tasks. The following section provides a review of studies that investigated factors associated with a binocular advantage during the performance of perceptual and motor tasks.

4.1.1 Binocular advantage in healthy adults during reaching and grasping movements

The binocular advantage has been studied during aiming and reach-to-grasp movements using kinematic measures (Coull, Weir, Tremblay, Weeks, & Elliott, 2000; Gnanaseelan, Gonzalez, & Niechwiej-Szwedo, 2014; Melmonth & Grant, 2006; Servos, Goodale, & Jakobson, 1992; Jackson, Jones, Newport, & Pritchard, 1991). Studies that examined simple aiming movements found a small binocular advantage for aiming (Coull, et al., 2000; Loftus, Servos, Goodale, Mendarozqueta, & Mon-Williams, 2004; Niechwiej-Szwedo, Goltz, Chandrakumar, Hirji, Crawford, & Wong, 2011a; Niechwiej-Szwedo, Goltz, Chandrakumar, Wong, 2012). In contrast, studies that examined grasping showed that binocular vision provides important information during reach deceleration and grasp application. In addition, some studies reported a lower peak velocity, a longer movement time, and a smaller or larger grip apertureduring monocular viewing (Melmonth & Grant, 2006; Servos, Goodale, & Jakobson, 1991; Gnanaseelan et al., 2014). In summary, binocular advantage is more evident for the grasping component, that is, when the participant has to manipulate an object during the performance of simple reach-to-grasp movement.

4.1.2 Binocular advantage in healthy adults during complex manipulation tasks

Research on the binocular advantage during complex manipulation tasks in visually-normal adults is limited. Only two studies in the literature examined complex manipulations tasks and their results suggest that the significance of binocular vision depends on task complexity (Read et al., 2013; Piano & O'Connor, 2013).

Read and colleagues (2013) examined the effect of using tools on the binocular advantage in participants aged between 7 and 82 years. Two tasks were used namely, the buzz wire task, and Morrisby manual dexterity task. In the buzz wire task, participants had to move a loop along a convoluted wire without touching the wire. In the peg-board task, participants inserted pegs into the holes of the board using their hands or using forceps to handle the pegs. Binocular advantage was calculated as the ratio between movement time obtained during dominant-eye viewing to that obtained during binocular viewing. Results showed that the binocular advantage was task dependent. Specifically, a greater binocular advantage (i.e., shorter movement time and fewer errors) was found in tasks that were performed with a tool in comparison to when manipulation tasks were performed directly with hands. Overall, these results suggest that binocular vision provides more accurate and/or precise information about the object's properties, which is especially important during manipulation tasks performed with a tool because direct haptic feedback about the properties of the object is not available. Thus, removal of direct haptic feedback when using a tool to manipulate an object places a greater demand on binocular vision to encode object's properties.

Piano and O'Connor (2013) examined the performance of bead-threading and water-pouring tasks while binocular vision was progressively degraded using convex lenses. Results showed that the effect of degraded binocular vision was more pronounced in the bead-threading task (large beads: 7%–10%, small beads: 0.5%–15%) than the water-pouring task (i.e., not significant). Thus, research indicates that the advantage of having inputs from both eyes seems to be task dependent in healthy adults. Specifically, binocular advantage in visually-normal adults is more pronounced in tasks where more precision is required or tasks where direct haptic feedback about the object is removed through tool use.

The studies by Read et al. (2013) and Piano and O'Connor (2013) provided an important contribution by showing that task precision and tool use are important factors that affect the extent of binocular advantage. However, these studies examined only 2 tasks and it is currently unknown how important binocular vision is during the performance of other manipulation skills. Thus, the main goal of this study was to extend the current literature on this topic and to characterize the binocular advantage during the performance of a range of different manipulation tasks.

4.1.3 Research objectives

The objective of this study was to examine the role of binocular vision during the performance of manual tasks that required tool use to manipulate an object in visually-normal adults. Specifically, we aimed to classify the tasks based on the extent of advantage afforded by binocular vision. A secondary objective was to determine the practice effects for the manipulation tasks during binocular and monocular viewing.

In study 1 of this thesis, we showed that the performance on the bead-threading task was more affected by removal of binocular vision in comparison to the peg-board task. Thus, the bead-threading task was used as a control task in the current study. The peg-board task was also included in this study to examine the binocular advantage when the task is performed using a tool to pick up the pegs. In addition to these control tasks (bead-threading and peg-board), two novel tasks involving tool-use were studied. These tasks involved using a tool to perform an aiming movement and using a tool to pick up a target and insert it into a hole

4.1.4 Hypotheses

Binocular vision will provide a greater advantage for the performance of tasks that require a tool to manipulate an object.

1. Movement time will be significantly shorter during binocular viewing compared to monocular viewing only when a tool is used to pick up the peg in order to transport it and place it precisely on the board in comparison to when the peg-board task is performed using the hand.

2. Movement time will be significantly shorter during binocular viewing only during the performance of a task where a tool is used to pick up the target in comparison to when the tool is used for aiming.

4.2 Method

4.2.1 Participants

Thirty-six young healthy adults ranging in age from 17 to 38 years (20 women, 16 men) were recruited from the University of Waterloo. All participants had normal or corrected-to normal vision with no history of neurological or visual disorders.

4.2.2 Experimental procedure

4.2.2.1 Assessment of visual functions

Visual acuity and stereoacuity were assessed using the same procedure used in study 1 (see section 2.4.2.1, 2.4.2.2). The eye that participants preferred to use for looking through the tube was defined as the dominant eye. Based on the assessment of visual acuity and stereoacuity, participants were included in the study only if they had normal or corrected-to-normal binocular and monocular visual acuity (i.e., at least 0.1 logMAR and interocular difference less than 0.2 logMAR) and normal stereoacuity threshold according to age norms (20-40 seconds of arc). One participant was excluded because she had a stereoacuity threshold of 70 seconds of arc.

4.2.2.2 Randomization protocol

Manipulation tasks were performed with the preferred hand, which was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971). The order of the tasks and viewing conditions was randomized as follows. The order of the tasks was first randomized using the RAND functions in Excel (Microsoft Office, 2010). Within each task, the level of difficulty was randomized. The three viewing conditions were randomized in two blocks. Block 1 began with binocular viewing, which was followed by dominant eye viewing, and then non-dominant eye viewing. Block 2 began with dominant eye viewing, which was followed by non-dominant eye, and then binocular viewing. The order of blocks was randomized and each participant performed 6 trials in all manipulation tasks. A binocular viewing practice trial was performed before the test trials for all the manipulation tasks. The randomization protocol is described in Figure 4.1. Overall, thirty-five adults performed all the five tasks, except the bead-threading task. Two participants did not complete the task with the same criteria applied to the full sample. They used beads with different criteria (bead colour and number) than that were used by the rest of the sample.

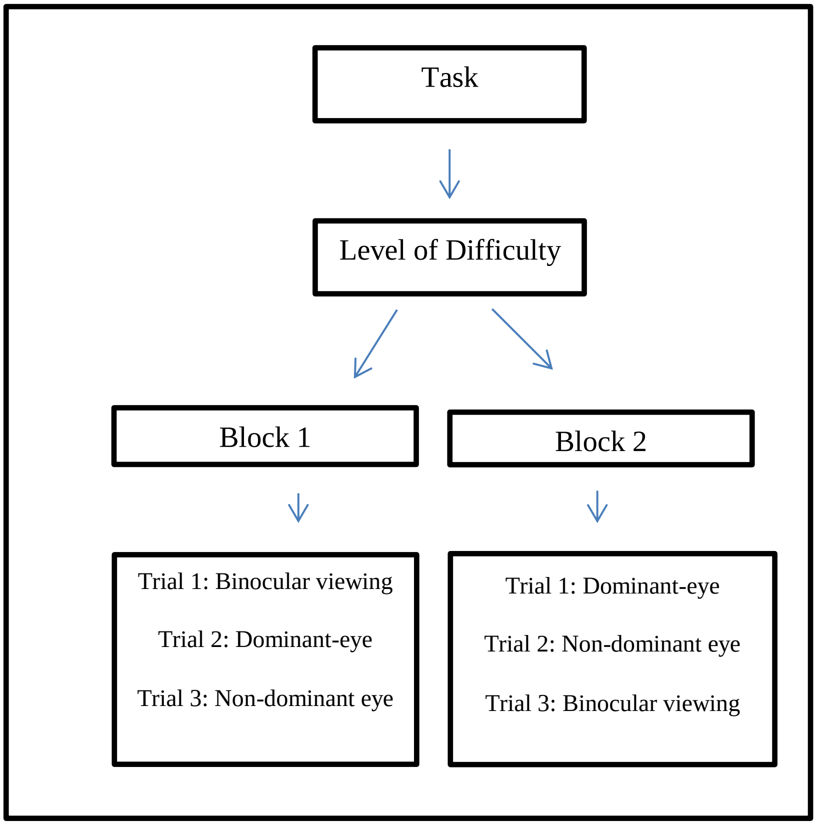


Figure 4.1: Schematic diagram for explaining the block design

4.2.2.3 Manipulation Tasks

4.2.2.3.1 Bead-threading task

This task was performed with the same equipment used in study 1. In contrast to study 1 where beads had different sizes, the beads had different size holes (i.e., 0.8 cm, 0.5cm). The main outcome measure was movement time, which was defined as the time elapsed between picking up the first bead and successfully placing the last one onto the needle. Movement time was measured with a stop watch.

4.2.2.3.2 Peg-board task

Participants picked up a peg that matched the peg size (diameter 0.3 cm and 0.6 cm) on the on the board, which was placed 20 cm in front of them. Participants performed this task using their hands and then using a tool (tweezers). Similar to the previous tasks, movement time was defined as the time elapsed between picking up the first peg until inserting the last one.

4.2.2.3.3 Pointing with a tool task

Participants performed the pointing task with a hand-held custom-made tool with a 20 cm needle-straight ending. The boards were wooden custom-made with 0.6 cm, and 0.3 cm holes that were spread in a 3x3 pattern. The board was supported on two wedges that placed it at an angle of 45º. Participants used the tool to point to the holes of the board and inserted the end of the tool in the hole. They were instructed to move from left to right, starting at the top row and then move to the next row. Movement time in this task was defined as the time elapsed between pointing to the first hole until pointing to the last hole.

4.2.2.3.4 Picking up a target using a hook tool (hook-task)

Participants performed the hook-task with a hand-held custom-made tool with a 20 cm needle-hook ending. The board was a wooden custom-made with 0.6 cm diameter holes arranged in a 3x3 pattern. The board was supported on two wedges that placed it at an angle of 45^o. The difficulty of this task was manipulated by using two kinds of targets: a ring (length= 2 cm, diameter= 1cm), or a hook (length= 1 cm, diameter= 1cm). Participants were asked to pick up the target and insert it into the holes of the board starting from the top row and moving from left to right. The main outcome for this task was movement time which was defined as the time elapsed between picking up the first target until inserting the last one, which was measured using a stop watch.

4.2.3 Analysis

The main objective of this study was to characterize the role of binocular vision in the performance of manipulation tasks involving tool use in visually-normal adults. First, we aimed to examine the significance of binocular vision in each task separately using movement time as the dependent variable. Before conducting the analysis of variance (ANOVA), paired t-tests conducted for each task to examine the difference between the dominant and non-dominant eye viewing. Results showed no significant difference between the dominant and non-dominant eye viewing for the peg-board with tool task (p=0.1), the peg-board with fingers task (p=0.98), and the pointing task (p=0.9). However, there was a significant difference between the dominant and non-dominant eye viewing for the bead-threading task (p=0.04) and for the hook-task (p=0.008). Because there was a significant difference between dominant and non-dominant eye viewing conditions in some of the tasks, the data were not collapsed for further analysis. The ANOVA was conducted for each task separately with three within-subject factors: Target Size (small and large), Viewing Conditions (binocular, dominant-eye, non-dominant eye), and Trial (1 & 2). In the peg board task, the Tool factor (Tool, No tool) was added as the fourth within-subject factor.

Second, the mean binocular summation was calculated as the ratio in movement time between binocular and the average monocular viewing (the average movement time obtained during dominant eye and non-dominant eye viewing). Binocular summation obtained in each of the ten tasks was compared using a one-way ANOVA. The trial with better performance (i.e., higher binocular summation ratio) was included in the analysis. Each task with a given target was considered as an independent task (i.e., large hole beads, small hole beads, large pegs with tweezers, small pegs with tweezers, large pegs with finger, small pegs with fingers, pointing to large holes, pointing to small holes, ring pins, hook pins). Additionally, the percentage of participants who showed a binocular advantage of ≥90%, which was defined as having a binocular summation ratio≤ 0.9, was calculated. All statistical analyses were performed using the SAS 9.4 software package and Excel (Microsoft Office, 2010). Descriptive statistics are reported as the mean and corresponding standard deviation. Any main effects and interactions were analyzed further using Tukey-Kramer post-hoc tests to adjust for multiple comparisons. The significance level was set at $p < 0.05$.

4.3 Results

4.3.1 The effect of tool use on movement time

4.3.1.1 Bead-threading task

Mean movement time in the bead-threading task during binocular, dominant eye and non-dominant eye viewing conditions is shown in Figure 4.2. The main effects of Viewing Conditions, Target Size, and Trial are reported in Table 4.1. Participants were slower when viewing monocularly compared to binocular viewing. Additionally, participants were faster with the large-hole-beads compared to the small-hole beads. However, there was no practice effect; participants were as fast in the first trial as in the second trial. The interaction between Viewing Condition and Target Size was used to examine the effect of changing the hole size, and this interaction was not significant ($F_{1,33}$=0.43, p=0.65). On average, a 3-seconds difference between binocular and both monocular viewing was found for both beads.

4.3.1.2 Peg-board with fingers vs. peg-board with tweezers

Results from the statistical analysis are reported in Table 4.1. The main effects showed that participants were slower when viewing monocularly compared to binocular viewing, slower when manipulating the small pegs compared to the large ones, faster in the second trial than in the first trial, and slower when using the tweezers to manipulate the pegs compared to when using fingers.

There was a significant interaction between presence of a tool and viewing condition ($F_{1,35}$=8. 57, p<0.0001), which suggests that the effect of viewing condition was greater when using the tweezers to manipulate the pegs (binocular viewing:23.65±4.85 s; dominant eye viewing: 27.34±7.06 s; non-dominant eye viewing: 26.78 ±6.74 s) compared to when fingers were used to manipulate the pegs (binocular viewing:13.81±1.83 s; dominant eye viewing:

15.40±2.75 s; non-dominant eye viewing: 15.28 ±2.20 s), as shown in Figure 4.3.

Lastly, there was no significant effect of Trial by Viewing Condition ($F_{1,35}$=2.97, p=0.0938). Overall, manipulating the pegs with tweezers results in relatively greater increase in movement time during monocular viewing compared to when the peg-board task was performed with fingers.

4.3.1.3 Pointing with a tool task

Results from the statistical analysis for the main effects of Viewing Condition, Target Size, and Trial are reported in Table 4.1. Similar to what was found in the bead-threading and peg-board tasks, participants were slower during both monocular viewing conditions compared to binocular viewing. Additionally, participants were faster when pointing to the large holes compared to when pointing to the small holes. Similar to the peg-board task, participants were faster in the second trial compared to the first trial. The interaction between Viewing Condition and Target Size was not significant ($F_{2,68}$=0.44 p=0.65), suggesting that removal of binocular vision had a similar effect when pointing to the large and to the small holes. In contrast to the bead-threading, the effect of viewing was much smaller. As shown in Figure 4.3, on average a 1 second difference between binocular and both monocular viewing conditions was found (binocular viewing: 8.62±1.48 s, 11.42±2.25 s, dominant eye viewing: 9.47±1.42 s, 12.50±2.53 s: non-dominant eye viewing: 9.54 ±1.58 s, 12.42 ±2.36 s, for pointing to large holes and small holes, respectively). Overall, the pointing task showed less sensitivity to binocular vision when compared with the bead-threading task.

4.3.1.4 Picking up a target using a hook tool (hook-task)

Mean movement time for the hook-task during binocular and monocular viewing is shown in Figure 4.5. Results from the statistical analysis for the main effects of Viewing Conditions, Target Size, and Trial are reported in Table 4.1. As expected, participants were slower during both monocular viewing conditions compared to binocular viewing. Furthermore, participants were faster when performing the hook-task with target 1 (i.e., ring pins) compared to target 2 (i.e., hook pins). Lastly, participants were faster in the second trial compared to the first trial.

An important question was whether performing the task with target 2 will show a greater effect of viewing. The interaction effect between Viewing Condition and Target Size was significant ($F_{2,68}$=3.7, p=0.03). As illustrated in Figure 4.5 and confirmed by a post-hoc test, movement time increased to a larger extent during monocular viewing compared to binocular viewing with the hook pin targets (binocular: 50.70±10.75 s, dominant eye viewing: 69.46±21.53 s, non-dominant eye viewing: 65.04 ±17.89 s) compared to the ring pin targets (binocular: 40.37±5.74 s, dominant eye viewing: 51.99±10.64 s, non-dominant eye viewing: 50.79±12.44 s). Additionally, the mean difference between the dominant eye and binocular viewing was greater in the hook pin targets (18.29 s) compared to the ring pin targets (11.75 s).

Another important question is whether learning effect occurs during monocular viewing. The interaction effect between Trial and Viewing Condition was not significant ($F_{2,68}=1.63$, $p=0.202$).

Table 4.1: Statistical results for the main effects and interaction effects in the hook, the bead-threading, peg-board and the pointing tasks

Task/Effect	**Viewing Condition**	**Target size**	**Trial**	**Target Size*Viewing**	**Trial*Viewing Condition**
Bead-threading task	($F_{2,64}=189.1$, $p<0.0001$)	($F_{1,32}=4.75$, $p=0.0368$)	($F_{1,32}=4.75$, $p=0.0368$)	($F_{2,64}=1.7$, $p=0.19$	($F_{2,64}=19$, $p=0.15$)
Peg-board with fingers vs. peg-board with tweezers	($F_{2,68}=71.88$, $p<0.0001$)	($F_{1,68}=103.68$, $p<0.0001$)	($F_{1,34}=19.96$, $p<0.0001$)	($F_{2,68}=2.76$, $p=0.07$)	($F_{2,68}=3.92$, $p=0.0245$)
			Tool: ($F_{1,34}=854.88$, $p<0.0001$)	Tool by Viewing: ($F_{3,102}=230.79$, $p<0.0001$)	Tool by Viewing by Target: ($F_{3,102}=6.52$, $p=0.0004$)

Pointing task	($F_{2,68}$=31.81, p<0.0001)	($F_{1,34}$=711.71, p<0.0001)	($F_{1,34}$=17.28, p=0.0002)	($F_{2,68}$=0.44 p=0.65)	($F_{2,68}$=2.82, p=0.067)
Hook-task	($F_{2,68}$=60.38, p<0.0001)	($F_{1,34}$=40.86, p<0.0001)	($F_{1,34}$=13.68, p=0.0008)	($F_{2,68}$=3.70, p=0.03)	($F_{2,68}$=1.63, p=0.202)

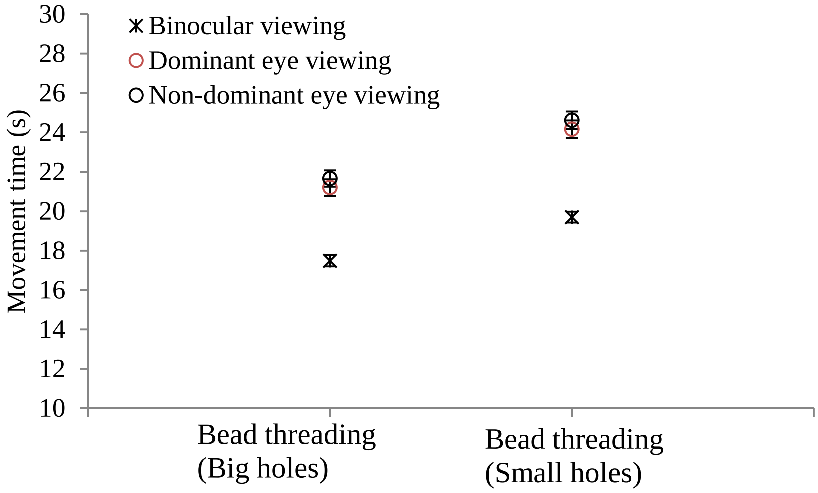


Figure 4.2: Mean movement time to complete the bead-threading task plotted for the beads with large holes and small holes during binocular and monocular viewing.

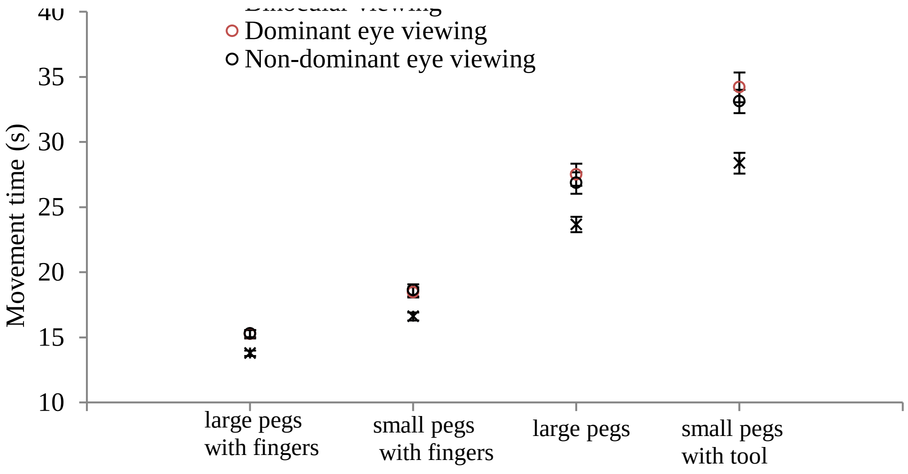


Figure 4.3: Mean movement time to complete the peg-board task plotted for the peg-board with fingers and tweezers during binocular and monocular viewing.

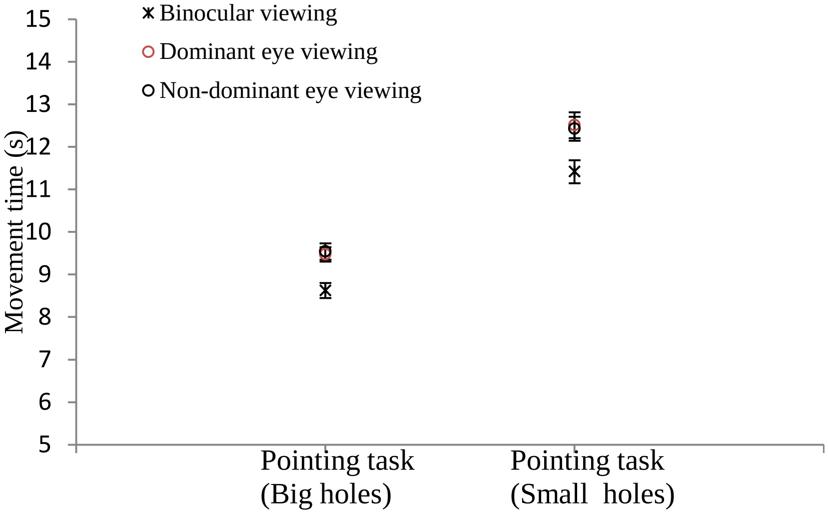


Figure 4.4: Mean movement time to complete the pointing task plotted for pointing to the large holes and small holes during binocular and monocular viewing.

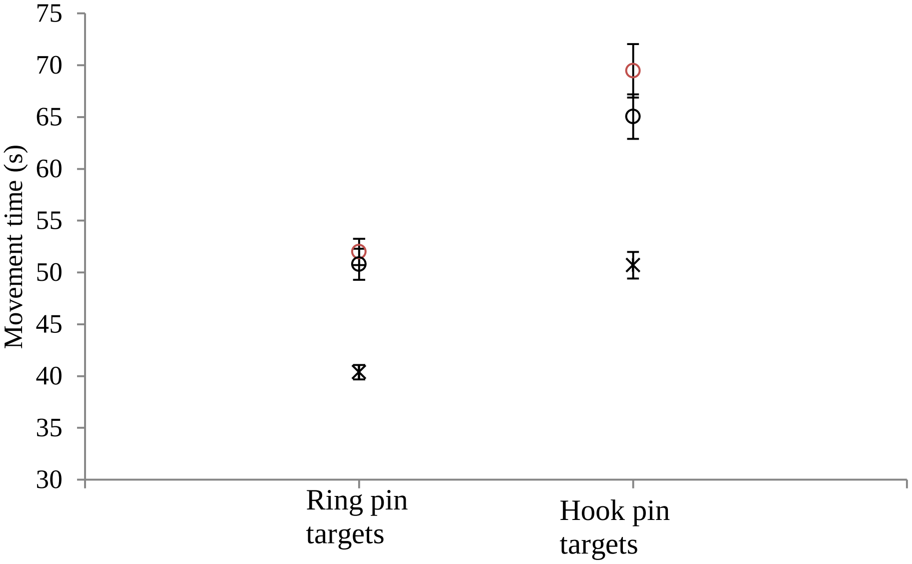


Figure 4.5: Mean movement time to complete the hook task plotted for ring pin targets and hook pin targets during binocular and monocular viewing.

4.3.2 The effect of task on the binocular advantage

After we examined the binocular advantage in each task separately, binocular summation was compared in order to characterize the difference in the binocular advantage across the ten manipulation tasks used in this study. Results from the ANOVA showed a main effect of task ($F_{9,350}=10.11$, $p<0.0001$). As shown in Figure 4.6 and confirmed by a post-hoc test, the mean binocular summation was similar in the pointing task with large holes (0.95±0.09), and small holes (0.98±0.10), the peg-board with fingers using the large pegs (0.95±0.09), the peg-board performed with tweezers using the large pegs (0.935±0.08), and the small pegs performed with tweezers (0.92±0.11). Furthermore, the binocular summation for the beads with large holes (0.87±0.08), and small holes (0.85±0.06) was similar to that of the hook-task with ring pin targets (0.86±0.11) and the hook-task with the hook pin targets (0.84±0.13) which was significantly different from the pointing task with the large and small holes, peg board with tweezers and the peg-board performed with fingers.

As shown in Figure 4.7, more participants showed a binocular advantage that was greater than 90% when performing the task involving the beads with small holes (75.0%) in comparison to the task involving the beads with large holes (69.4%). The percentage of participants who showed a binocular advantage was greater with the ring pin targets (75.0%) than with the hook pin targets (69.4%). The percentage of participants who showed an advantage of greater than 90% was equal in the large pegs with tweezers and in the large pegs with fingers (30.6%). However, the percentage of participants who showed a binocular advantage was greater in the small pegs with tweezers (50.0%) than in the small pegs with fingers (22.2%). In the pointing task, fewer participants showed an advantage greater than 90% when pointing to the small holes (22.2%) compared to pointing to the large holes (36.1%). These results further confirm the above-reported results about the high sensitivity of the hook-task and the bead-threading task, moderate sensitivity of the peg-board with tweezers, and minimal sensitivity to binocular vision for the peg-board task performed with fingers and the pointing task.

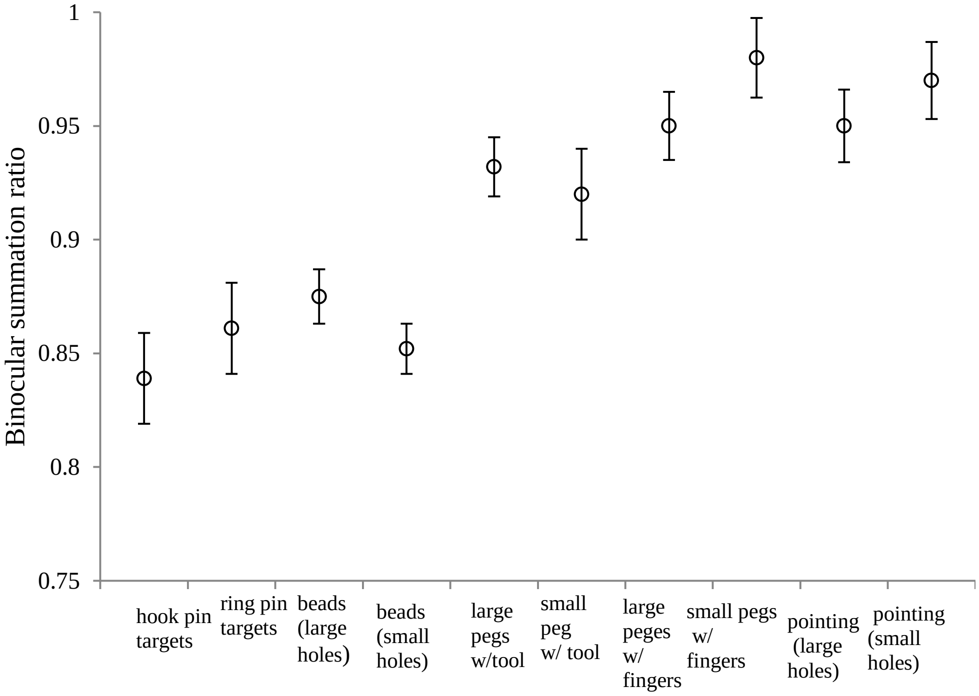


Figure 4.6 Mean binocular summation ratio in the ten tasks.

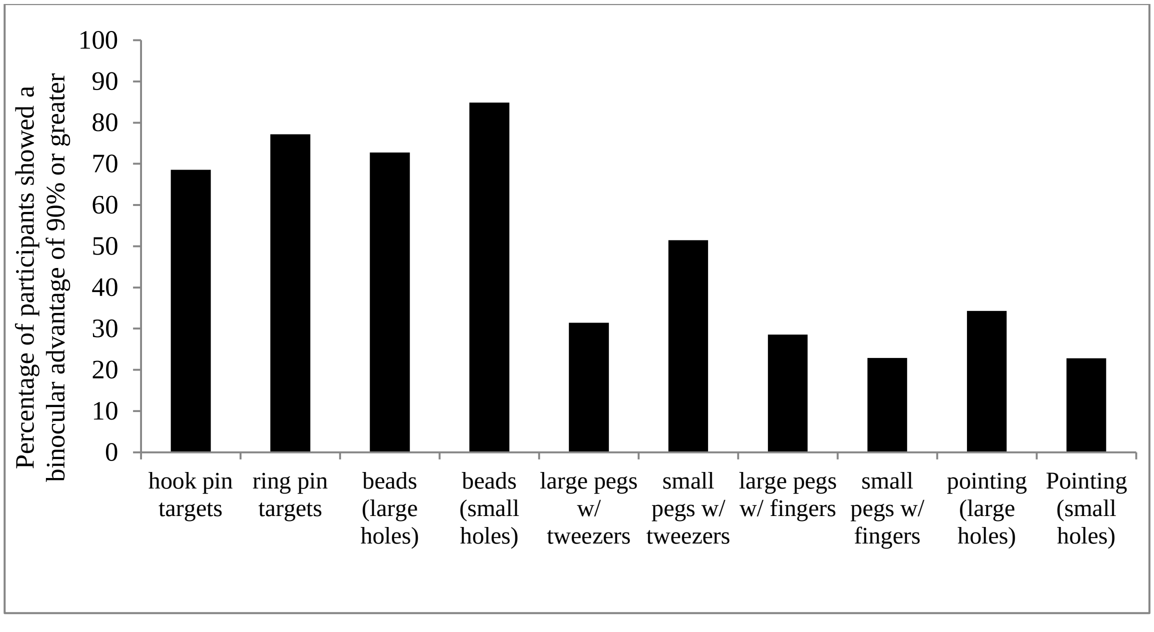


Figure 4.7: the percentage of participants who showed a binocular advantage of≥ 90%. Note, the higher the bar is, the higher the binocular advantage in a given task.

4.4 Discussion

The main finding from this study is that tasks that require precise manipulation of small targets either using hands (i.e., bead-threading task) or using a tool (i.e., the hook-task with the ring pin targets or the hook pins targets) are more dependent on binocular vision. Adding a tool to the peg-board task also resulted in a relatively greater increase in movement time during monocular viewing compared to when the peg-board task was performed with fingers where the difference in movement time between binocular and monocular viewing was quite small. However, when comparing the binocular summation ratio of the peg-board with tweezers, it seems that this task is less dependent on binocular vision compared to the bead-threading and the hook tasks. In contrast to the peg-board with tweezers vs. that with fingers, adding a tool to perform a localization task (i.e., pointing) did not result in a large performance difference during monocular viewing.

The structure of the tool and the target play a role in determining the binocular advantage of a given task. Our results showed that the hook-task had a higher binocular advantage compared to the peg-board task performed with tweezers. This difference may be due to the properties of the target or the tool. The pegs were larger and had a cylindrical shape, therefore they could be picked anywhere along the shaft with tweezers. In contrast, the targets that were used in the hook-task, (i.e., the hook pin targets and the ring pin targets),were smaller and they had to be picked up using a tool oriented in a specific direction. Furthermore, the board in the hook-task was placed at an angle of 45º which requires more depth perception to resolve the location of the holes of the board. In the case of the peg-board performed with tweezers, the holes of the board were aligned in a horizontal plane, which is much easier to locate during monocular viewing. Such finding agrees to that of Ozkan and Braunstein (2010) who found that participants were slower in localizing the target when the target was placed in a slanted surface over the ground surface. It is possible that participants required a longer time to encode the location of the hole on the slanted board than when the board was placed on a horizontal plane. Overall, the precision requirement was higher in the hook task than in the peg-board performed with tweezers, which contributed to the higher binocular advantage of the hook task.

The tool and the board were similar in the hook-task and the pointing task, but the binocular advantage was much lower in the pointing task than the hook-task. In the pointing task, participants aligned the tool to the holes on the board. In the hook-task, participants picked up a target with the tool and then had to place it precisely in the holes on the board. Thus, the main difference between the pointing task and the hook task was that the tool was used to pick up a target prior to placing it in the hole. These results emphasize that binocular vision provides important information about the properties of the target object, for example, its shape and orientation, which is critical for planning how to grasp an object.

Lastly, the binocular advantage was similar between the hook-task and the bead-threading task. The alignment of the bead's hole to the needle placed a similar demand on the binocular vision system. Similarly, removing the haptic feedback by adding the hook tool to pick up the screws and inserting them into the holes of the board was the most difficult aspect of the hook task.

4.4.1 Conclusions and future directions

In conclusion, the manipulation tasks that were used in this study can be classified in terms of a binocular advantage into tasks with high, moderate and minimal binocular advantage.

Tasks with high binocular advantage are the bead-threading and the hook task. The task with moderate binocular advantage is the peg-board task performed with tweezers. Tasks with minimal binocular advantage are the pointing with a tool task and the peg-board task performed with fingers. Thus, binocular advantage is more evident in tasks where precision is required for picking up and placing the target, which increased to a large extent when haptic feedback was removed through tool-use.

The significance of binocular vision during the performance of fine motor skills that vary in complexity is important to be addressed from the occupational point of view. Binocular vision is essential in certain jobs where small objects need to be localized and manipulated skilfully, for example, surgeries, dental procedures, and mechanical manipulation. Healthy binocular vision might be one of the requirements to be qualified for these occupations. Otherwise, reduced binocular vision might result in either reduced job efficiency or increased risk of injury. Additionally, classification of motor tasks based on the significance of binocular vision is important and should be addressed in the field of occupational rehabilitation. Occupational therapists should take into account the importance of binocular vision during the performance of complex manipulation skills. For instance, including a full binocular vison assessment (i.e., stereoacuity, accommodation, and vergence) for patients who are referred for rehabilitation of fine motor skills may be helpful in order to determine the status of the system that has an important contribution to the performance of skilful movements. Because performance of fine motor skills might relate to having abnormal binocular vision, it should be assessed before implementing a rehabilitation program.

Chapter 5: Conclusion

5.1 Conclusions and future directions

The findings from this thesis advance our knowledge about the role of binocular vision in the performance of complex manipulation tasks in school-aged children and adults. The tasks that we have chosen are used commonly in occupational therapy during assessment and rehabilitation of fine motor skills in children and adults. However, the status of binocular vision is not typically assessed prior to the rehabilitation of skilful movements. Results from this project provide evidence to support that normal binocular vision provides important sensory input during the development and performance of fine motor skills. One important implication from this research is that fine motor skills should be assessed in children with abnormal binocular vision (i.e., children with amblyopia and strabismus, 2-3% of population). Furthermore, results from study 2 of this thesis highlight the importance of including a full assessment of binocular vision and fine motor skills in children with learning difficulties. Lastly, results from study 3 characterized manipulation tasks based on the significance of binocular vision and showed that this sensory input is critical for the performance of tasks that require precise object manipulations when using hands directly or when using a tool. These findings have implications for occupational performance. Specifically, a binocular vision assessment may help to identify persons who are likely to have reduced performance on fine motor tasks that require object manipulations. In the cases where abnormal binocular vision is evident, management of binocular vision should be addressed before delivering an occupational training or a rehabilitation program.

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