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Contribution of stereopsis, vergence, and accommodative function to the performance of a precision grasping and placement task in typically developing children age 8–14 years

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ABSTRACT

Upper limb reaching and grasping movements are performed more efficiently during binocular viewing; however, the distinct contribution of stereopsis, fusional vergence, and accommodation (binocular facility, amplitude and accuracy) has not been examined in typically developing children. This study examined binocular visual function in a cohort of 57 typically developing children, 8 to 14 years old. Hand kinematics were recorded using a motion capture camera while children performed a prehension task involving threading a bead onto a needle. Results showed that different aspects of binocular vision contribute to the control of distinct phases of upper limb movements. Specifically, fusional vergence was associated with higher peak reach velocity, stereoacuity was associated with shorter grasp execution, and accommodation was associated with shorter placement duration. These findings suggest that different aspects of binocular vision play an important role in optimizing the control of distinct phases of prehension movements during development.

1. Introduction

Normal binocularity provides important input for the planning and execution of upper limb movements, such as reaching and precision grasping in adults (Fielder & Moseley, 1996; Grant, Melmoth, Morgan, & Finlay, 2007; Jones & Lee, 1981; Melmoth & Grant, 2006; Servos, Goodale, & Jakobson, 1992). Furthermore, research demonstrated that fusional vergence and stereoacuity are associated with the control of distinct phases of a prehension movement, namely, reach (i.e., transport) and grasp (Melmoth, Storoni, Todd, Finlay, & Grant, 2007; Mon-Williams & Dijkerman, 1999). In typically developing children, binocular viewing is also associated with improved performance of prehension (Alramis, Roy, Christian, & Niechwiej-Szwedo, 2016), which is more evident in older children (Suttle, Melmoth, Finlay, Sloper, & Grant, 2011; Watt, Bradshaw, Clarke, & Elliot, 2003). Given that improvements in binocular vision extend beyond the first decade (Giaschi, Narasimhan, Solski, Harrison, & Wilcox, 2013), it is possible that maturation of binocular vision contributes to improved fine motor skill performance. However, it is currently unknown whether stereoacuity and fusional vergence provide a distinct contribution to the control of reaching and grasping in children. Therefore, the goal of this study was to assess the contribution of stereopsis, fusional vergence, and accommodation to the performance of a precision manipulation task in typically developing children, 8 to 14 years old.

Binocular viewing is associated with improved performance of fine motor skills in adults and children with normal vision (Alramis

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et al., 2016; Gnanaseelan, Gonzalez, & Niechwiej-Szwedo, 2014; Marotta & Goodale, 2001; Melmoth & Grant, 2006; Read, Begum, McDonald, & Trowbridge, 2013; Servos et al., 1992; Watt & Bradshaw, 2000). In adults, binocular advantage is most evident during the reach deceleration phase and grasp application, where these two aspects of prehension are executed faster, more accurately, and more precisely, when viewing with both eyes (Bradshaw & Elliott, 2003; Gonzalez & Niechwiej-Szwedo, 2016; Jackson, Jones, Newport, & Pritchard, 1991; Servos & Goodale, 1994). In contrast, some studies failed to detect a binocular advantage for tasks such as pointing (i.e., reach without grasp) (Bennett, Elliott, Weeks, & Keil, 2003; Niechwiej-Szwedo, Goltz, Colpa, Chandrakumar, & Wong, 2017), relatively simple prehension movements, such as a peg board or water pouring (O'Connor, Birch, Anderson, & Draper, 2010; Piano & O'Connor, 2013), or when the target is presented at certain viewing angles (Keefe & Watt, 2017). These results suggest that improvement in motor performance associated with binocular viewing may be task dependent in adults.

In typically developing children the extent of binocular advantage is both age and task dependent. For example, Watt and colleagues assessed the reach kinematics in younger (5–6 years old) and older (10–11 years old) children, and found no significant difference in peak reach velocity, or grip aperture, between binocular and monocular viewing in both age groups during a task that involved reaching and grasping a wooden block (Watt et al., 2003). Interestingly, like adults, Watt et al. found that older children spent more time in the deceleration phase when binocular vision was removed; however, grasp duration was not reported in that study. These results indicate that binocular vision provides a greater advantage in older children, which may arise due to improved binocular vision, and the ability to use that sensory information to control upper limb movements. Notably, a large body of research demonstrates developmental changes in sensorimotor control strategies, where 5–7 year old children tend to perform movements ballistically and rely mainly on feedforward control, whereas 8–10 year old children begin to use online feedback (Hay, 1979; Smyth, Peacock, & Katamba, 2004). Finally, adult-like sensorimotor control, emerges during the early teenage years, which is characterized by optimal interface between feedforward and feedback control. In the context of these studies, it is possible that binocular advantage is more evident in the older compared to the younger children, because the ability to use feedback during reach execution increases with age (Grant, Suttle, Melmoth, Conway, & Sloper, 2014b; Suttle et al., 2011).

Task dependent effects on prehension performance were reported in a study which evaluated the contribution of binocular input using two challenging tasks, peg board and bead threading (Alramis et al., 2016). Results showed that binocular viewing was associated with a small improvement in the performance of a peg board task in children, which is consistent with the results found by Watt et al. (2003). In contrast, children showed a large binocular advantage in the performance of a bead threading task, which was also seen in adults. Overall, these results highlight the importance of choosing appropriate tasks to study the role of binocular vision in the development and control of upper limb movements.

Most studies that examined the contribution of binocular vision to prehension performance manipulated viewing conditions such that performance was examined under binocular or monocular viewing, and therefore cannot differentiate between the contribution of stereopsis or vergence eye movements to motor control. To date, only a few studies manipulated stereopsis and vergence to assess their unique contributions to prehension (Melmoth et al., 2007; Mon-Williams & Dijkerman, 1999). Results showed that reducing stereopsis using convex lenses disrupted the execution of grasping, while disrupting fusional vergence using base out or base in prisms, was associated with a misestimation of target distance and reaching errors. These studies, however, were performed with adults, and therefore the contribution of stereopsis and vergence to the development and control of upper limb movements in children remains to be established.

Binocular stereopsis is the ability to see depth based on the horizontal disparity of the images (i.e., binocular disparity) (Harris, 2004), while stereoacuity threshold is the smallest depth difference that subjects can detect. Stereopsis emerges around 12–16 weeks of age (Birch, Gwiazda, & Held, 1982; Braddick, 1996), and continues to improve over the first decade of life (Afsari et al., 2013; Ciner et al., 2014) or beyond (Giaschi et al., 2013). It provides information about relative depth, which is important for encoding an object's properties, such as its size, shape, orientation or texture, and may be involved in programming appropriate grip aperture and grasp forces. Consistent with this idea, adults and children with abnormal binocular vision and poor stereopsis due to amblyopia tend to have a larger grip aperture and longer grasp duration (Grant et al., 2007, 2014b).

The motor aspect of binocular vision is horizontal fusional vergence, which refers to convergent and divergent eye movements to fixate stimuli that are at different distances in depth (Howard & Rogers, 2002). Fusional vergence develops postnatally at approximately 3 months of age (Aslin, 1977; Bharadwaj & Candy, 2008), and is stimulated by a retinal disparity between the two eyes, in order to achieve single binocular vision. Although the gain, peak velocity, and duration of vergence movements are similar to adults by 4 years of age (Yang & Kapoula, 2004), the latency of vergence response continues to improve, and becomes adult-like around the age of 10–12 years (Yang, Bucci, & Kapoula, 2002).

Accommodation is tightly coupled with vergence (Howard & Rogers, 2002). Blur is the stimulus that drives the accommodation system, and the accommodative response can be measured under binocular and monocular conditions. Under normal viewing conditions, convergence is associated with increased accommodation when fixating at a near object, and divergence is associated with decreased accommodation when fixating at a farther distance. The two systems are neurally coupled, and work together to maintain clear vision (Ciuffreda, Wang, & Vasudevan, 2007). Because retinal blur is the stimulus that activates the accommodative system, the development of accommodation is linked with the maturation of visual acuity (Banks, 1980). In fact, a reciprocal dependency has been proposed to explain that improvement in visual acuity relies on accurate accommodative input, and conversely, accommodative accuracy improves with maturation of visual acuity. Improvements in visual acuity and accommodative accuracy are well documented in infants and young children (Leat, Yadav, & Irving, 2009). Importantly, a more efficient accommodative system has been linked with improved performance of the bead threading task in 5–12 year old children with reading difficulties (Niechwiej-Szwedo, Alramis, & Christian, 2017). Additionally, a poor accommodative function has been reported in a cohort of children diagnosed with a developmental coordination disorder, suggesting that accommodation might be contributing to deficits in fine motor skills (Rafique & Northway, 2015).

To summarize, research shows that in comparison to monocular viewing, binocular viewing is associated with faster, more accurate and precise performance of reaching and grasping movements in adults and children. Perturbation paradigms have been used with adults to reveal that different aspects of binocular vision contribute to the control of distinct phases of upper limb movements. However, it is currently unknown if different components of binocular vision contribute to the control of distinct phases of upper limb movements in typically developing children. Our previous work has shown that performance of the bead threading task stops improving around 10 years of age (Niechwiej-Szwedo et al., 2020), however, there was a significant amount of variability among individual children, such that the confidence intervals for the age when performance stopped improving ranged between 8 and 11 years. The only aspect of binocular vision assessed in that study was stereoacuity, and regression analysis revealed that lower stereoacuity thresholds were associated with a higher peak reach velocity, and shorter deceleration interval duration. The present study was designed to extend these findings by including a more comprehensive binocular vision assessment, involving stereoacuity, fusional vergence, and accommodation. It was expected that better binocular vision will be associated with improved performance of a precision grasping and placement task. More specifically, and in accordance with the results from previous studies with adults (Melmoth et al., 2007) and children (Niechwiej-Szwedo et al., 2020; Rafique & Northway, 2015), it was hypothesized that a lower stereoacuity threshold is associated with more efficient reaching and grasping, whereas fusional vergence is associated with the control of reaching (peak reach velocity), and accommodation is associated with overall task performance.

2. Methods

2.1. Participants

Participants were recruited from the University of Waterloo Optometry Clinic, and the local community. The cohort included 57 typically developing children between the ages of 8 and 14 years (26 males, age: 10.74 ± 2.03 years; 31 females, age: 10.63 ± 1.93 years). Children with neurodevelopmental disorders were excluded from the study. Four of the children were left-handed, which was obtained from the parental report.

2.2. Procedures

The study was reviewed and received clearance through the Research Ethics Committee in accordance with the Declaration of Helsinki. Written consent was obtained from all parents or legal guardians, and all children completed an assent form. Testing was conducted in a well-lit and quiet laboratory room. The experimental protocol consisted of a visual assessment performed by a registered optometrist, and an assessment of fine motor skills using the bead threading task. The order of assessments was counterbalanced across participants.

2.2.1. Visual function assessment

All visual and binocular testing was assessed with the child's habitual correction (if applicable). Distance visual acuity (6 m) was measured using the Bailey-Lovie visual acuity chart and the Lighthouse Continuous Text Card for Children was used to measure visual acuity at near (0.4 m). Acuity was defined as the line where 3 out of 5 letters were reported correctly.

Stereoacuity was measured using the Randot® Stereoacuity Test (Stereo Optical Company, Chicago USA) following the publisher's guidelines. The unilateral and alternating cover test at distance (6 m) and near (0.4 m) determined the presence and amount of ocular deviation, and was measured using an accommodative target 2 lines above best visual acuity with the eyes in primary position.

Horizontal fusional vergences were measured in free space using prism bars, and a 0.5 m vertical line at 0.4 m. Vergence facility was performed by asking the child to view a 20/30 vertical column at 0.4 m. A 12BO/3BI prism flipper was interchangeably placed in front of the child as they focused on the vertical column for a period of 1 min. The outcome measure is the number of times the child reported the vertical column was clear and single, and was recorded as cycles per minute (cpm).

Binocular accommodative facility (BAF) was assessed using the 20/50 Bernell Accommodative Rock Card at 0.4 m, and ± 2.00 D lenses for a period of 1 min. For BAF, a suppression check was used to ensure binocularity. Accommodative amplitude was measured by the push-up method and a 0.6 m letter and calculated using the Duane-Hoffstetter minimum amplitude equation (15.0–0.25 × age). Accommodative accuracy was assessed by monocular estimation method (MEM) retinoscopy and using an age-appropriate target. All binocular vision and accommodative results were classified according to normative data described by Scheiman and Wick (2008), except for vergence facility (Gall, Wick, & Bedell, 1998), amplitude of accommodation (Hofstetter, 1950), and stereoacuity (Birch, Williams, Drover, Fu, & Cheng, 2008) (Table 1).

2.2.2. Motor skill assessment

The bead threading task was performed with the preferred hand, and viewing was binocular. Two infrared markers were placed on the thumb and index finger of the preferred hand, and the Optotrak motion capture system (NDI, Waterloo, ON) was used to record limb position at a sampling frequency of 250 Hz. Children were seated with their chin in a chinrest, and the bead threading apparatus directly in front and aligned with their midline (Fig. 1). The vertical needle (height: 12 cm; diameter: 0.3 cm) was placed 15 cm in front of the chinrest, and the bead holder was placed 20 cm in front of the needle. This set up ensured a comfortable reaching distance for all children. The bead (diameter: 1.0 cm; hole diameter: 0.5 cm) was placed on the holder by the experimenter. At the beginning of each trial, children were asked to place their index finger and thumb at the tip of the needle, and to look at the

Table 1
Expected clinical findings.

Clinical test	Expected finding (value ± SD)
Visual acuity (logMAR)	0.00 ± 0.10
Stereopsis (*sec* of arc)	40
Phoria (prism diopter [PD])	Distance: 1Exo ± 2Δ
	Near: 3Exo ± 3Δ
Positive fusional vergence (base out) near (PD)	Break:23 ± 8Δ
	Recovery:16 ± 6Δ
Negative fusional vergence (base in) near (PD)	Break:12 ± 5Δ
	Recovery:7 ± 4Δ
Vergence facility (cycles per minute [cpm]_	16 ± 2.6
Binocular accommodative facility (cpm)	5 ± 2.5
Amplitude of accommodation (D)	15.0–0.25 × age
Monocular estimation method (MEM) (diopter [D])	+0.50 ± 0.25

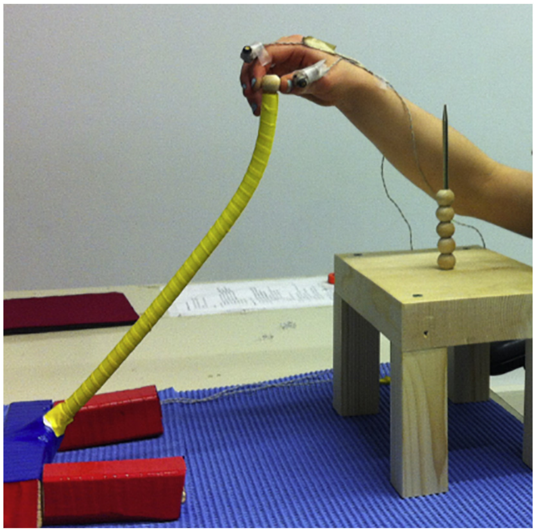

Fig. 1. Experimental set up for the bead threading task.

needle. An auditory beep was used as a 'go' signal to initiate the bead threading task, which consisted of reaching towards the bead, grasping, transporting, and placing the bead on the needle. Children were instructed to do this task as fast as possible without dropping the beads. Each child completed at least 8 practice trials prior to data collection. Following practice, children completed 30 consecutive bead threading trial, which took approximately 10–15 min.

2.3. Analysis of kinematic data

The raw kinematic data were first filtered using a low-pass second order Butterworth filter with a cut-off frequency of 10 Hz. The filtered data were used to obtain a velocity trajectory using a two-point differentiation. A custom written Matlab script identified the initiation and termination of reaches towards the bead and towards the needle using velocity criteria. Reach initiation was detected when the index finger velocity exceeded 0.030 m/s for 20 ms, and reach termination was detected when finger velocity dropped to 0.100 m/s. Each trial was visually inspected to ensure that movement initiation and termination for each reaching movement (i.e., towards the bead and towards the needle) were identified correctly by the script. These time points were subsequently used to calculate the following outcome measures, illustrated in Fig. 2: 1) reach-to-bead duration, defined as the interval from reach initiation to reach termination; 2) peak velocity of the reach to bead, defined as the maximum velocity along the depth direction; 3) grasp duration, defined as the interval from reach termination to when the subsequent reach towards the needle was initiated; 4) reach-to-needle duration, defined as the interval following grasping when the reach towards the needle was initiated to reach termination; 5) peak velocity of the reach to needle, defined as the maximum velocity along the depth direction; 6) placement duration, defined as the interval following reach termination to when the hand moved away from the needle after the bead was placed on it (children were instructed to move their hand away from the needle after the bead was placed); 7) total time to complete a bead threading trial was defined as sum of the components: reach-to-bead, grasp, reach-to-needle, and place. The time of peak velocity was used to define the duration of the acceleration and deceleration intervals for each reaching movement, which were defined as the time from reach initiation to the time of peak velocity, and the time of peak velocity to reach termination, respectively.

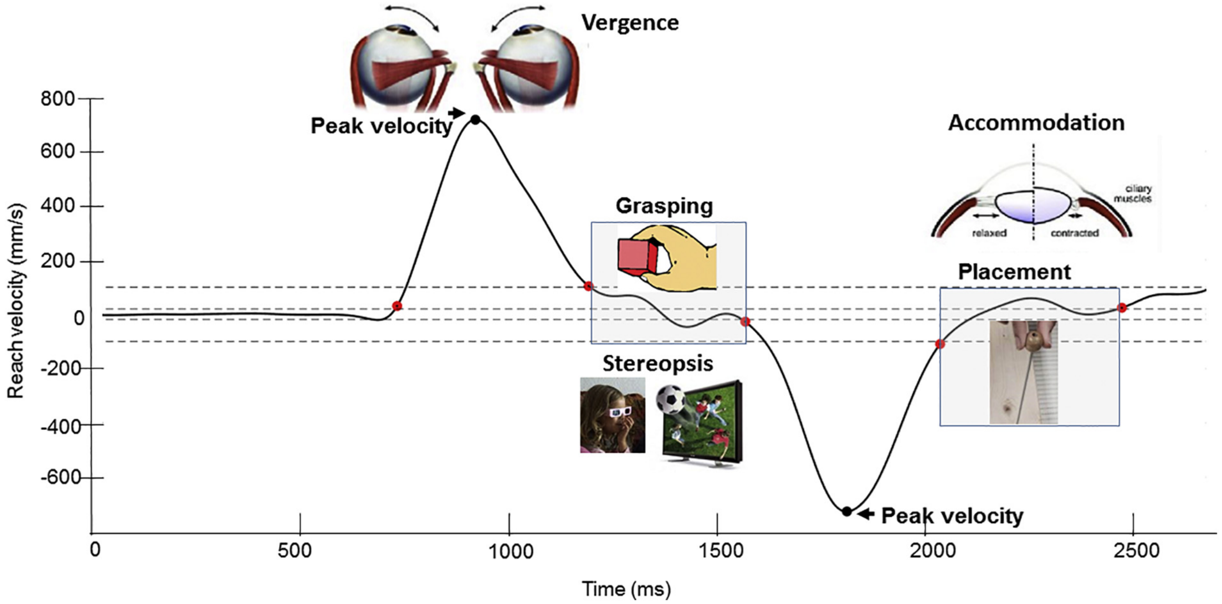

Fig. 2. Typical reach velocity trajectory recorded during the performance of a bead threading task. Components of the bead threading task were defined using velocity criteria (i.e., reach to bead, grasping, reach to needle, and placement), the initiation and termination of each reaching movement is identified by the red circles, grasping and placement are depicted by the shaded area. Peak velocity for reaching to the bead and to the needle is depicted with the black arrow. Higher peak reach velocity was associated with better vergence function. Lower stereoacuity thresholds were associated with shorter grasp duration. Better accommodative function was associated with shorter placement duration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4. Statistical analysis

Analysis was performed using SAS Studio (3.6 Enterprise Edition). First, Pearson's correlations were computed among the visual function measures to determine the degree of association between these measures and their association with age. Correlations were also computed to assess the association between kinematic measures from the bead threading task, age, and gender. These correlations were performed first so that the results from the current study could be compared to previous studies that separately examined the effects of age on visual function or motor performance.

To address the main goal of the current study, a stepwise multiple regression analysis was used to determine the contribution of the different components of binocular vision to motor performance (Hocking, 1976). More specifically, this analysis aimed to determine the influence of visual acuity, phoria, stereoacuity, horizontal fusional vergence, vergence facility, binocular accommodative facility, accommodative amplitude and accuracy amplitude of accommodation on motor performance. Since age has been associated with improvements in motor performance, the regression model included age as a predictor to ensure that the association between motor performance and binocular vision is not simply due to age. The variance inflation factor (VIF) was used to assess the threat of multicollinarity. The final regression model included only the predictors that explained at least 5% of variance in bead threading performance for all the motor performance outcome measures. Results are reported as means with corresponding standard deviation, Pearson's correlation coefficients with the corresponding 95% confidence intervals, and the amount of explained variance, R^2, for each significant predictor.

3. Results

3.1. Vision assessment

Results from the visual assessment are summarized in Table 2. In general, the results were in line with normative data summarized in Table 1. First, a Pearson's correlation analysis was conducted to examine the association between measures of binocular vision and age. Vergence facility was the only measure that was moderately, but significantly associated with age, $r\,(56) = 0.29$, 95% CI [0.03, 0.51, $p = .026$). The association between different measures of visual function and age is shown in a Supplementary Table 1. Because the correlations between the right and left eyes for amplitude of accommodation and accommodative accuracy were very high ($r \geq 0.95$), the average value across the right and left eyes were used in the multiple regression analysis. Similarly, only fusional vergence break values were used in the multiple regression analysis since the correlations between positive fusional vergence break and recovery ($r \geq 0.89$), and between negative fusional vergence break and recovery ($r \geq 0.86$) were also high.

Table 2
Summary of results from the binocular vision assessment.

Clinical test performed	Mean ± SD (range)
Visual acuity (logMAR) distance / near	-0.02 ± 0.07 (-0.10–0.18)/0.01 ± 0.03 (0.00–0.18) Snellen range: 20/15–20/25
Stereopsis (*sec* of arc)	24 ± 7 (20–50)
Phoria (PD) distance / near	1.8 ± 5.4 ($0-22$) / 2.4 ± 4.0 (0–18)
Positive fusional vergence (BO, convergence) near - break / recovery (PD)	24 ± 10 (8–45) / 18 ± 11 (2–45)
Negative fusional vergence (BI, divergence) near - break / recovery (PD)	14 ± 4 (4–25) / 11 ± 4 (4–20)
Vergence facility (cpm)	14 ± 4 (5–24)
Binocular accommodative facility (cpm)	8 ± 3 (0.5–14.5)
Amplitude of accommodation – OD and OS (D)	11 ± 2 (7–16) / 11 ± 2 (6–16)
Accuracy of accommodation (MEM) – OD and OS (D)	1.06 ± 0.40 (0.25–2.00) / 1.06 ± 0.40 (0.25–2.00)

BO: base out; BI: base in; D: diopters; PD: prism diopter; MEM: monocular estimate method; cpm: cycles per minute.

3.2. Bead threading assessment

Table 3 shows a summary of results for the kinematic measures recorded during the bead threading task, as well as their association with age and gender. The association was assessed using a Pearson's correlation coefficient. Results are consistent with a previous study with a larger cohort of children tested on the bead threading task (Niechwiej-Szwedo et al., 2020). Older children completed the task faster, r (56) $= -0.46$, 95% CI [-0.23, -0.64, $p < .0001$). Older age was also associated with a shorter grasp duration, r (56) $= -0.30$, 95% CI [-0.04, -0.52, $p = .021$), and a shorter placement duration, r (56) $= -0.52$, 95% CI [-0.30, -0.69, $p < .0001$). In contrast, gender was not significantly associated with the performance of bead threading.

3.3. Association between binocular visual function and bead threading performance

Fig. 2 provides a schematic illustration of when during the reach trajectory the contribution of stereopsis, fusional vergence, and accommodation is significant. Importantly, for the regression model with multiple predictors that included age, the VIF was < 2 indicting that the risk of multicollinearity was low. Only results significant at $p < .05$ are presented below.

3.3.1. Stereopsis

Results from the stepwise multiple regression showed that stereoacuity threshold was the only predictor in the regression model that explained > 5% of variance. Specifically, 16% of variance in grasp duration was explained by stereoacuity ($R^2 = 0.16$, F (1,55) = 10.19; $\beta = 0.39$, $p = .002$). In contrast, age explained only 4% of variance ($p = .0933$). Using the estimates from our regression analysis, results show that grasp duration is ~150 ms for children with stereoacuity of 20 arc *sec*. In comparison to this group, grasp duration increased by 80 ms for children with 40 arc sec stereoacuity, and by 190 ms when stereoacuity is 50 arc sec.

3.3.2. Horizonal fusional vergence and vergence facility

Results showed that vergence was associated with higher peak reach velocity, and explained 15% of variance ($R^2 = 0.15$, F

Table 3
Summary of results for the kinematic measures from the bead threading task, as well as their association with age and gender.

Bead threading measures	Mean ± SD	Association with age	Association with gender
Total movement time (ms)	1551 ± 302	$r = -0.46$ **p < .001**	$r = -0.15$ $p = .276$
Peak velocity (m/s)	0.886 ± 0.137	$r = 0.21$ $p = .117$	$r = -0.14$ $p = .312$
Reach duration (ms)	411 ± 48	$r = -0.16$ $p = .237$	$r = -0.06$ $p = .618$
Grasp duration (ms)	173 ± 78	$r = -0.30$ **p = .021**	$r = -0.05$ $p = .703$
Placement duration (ms)	559 ± 190	$r = -0.52$ **p < .0001**	$r = -0.17$ $p = .201$
Reach-to-bead acceleration interval duration (ms)	182 ± 32	$r = 0.01$ $p = .933$	$r = 0.04$ $p = .744$
Reach-to-bead deceleration interval duration (ms)	236 ± 34	$r = -0.14$ $p = .299$	$r = -0.05$ $p = .691$
Reach-to-needle acceleration interval duration (ms)	212 ± 32	$r = -0.27$ **p = .039**	$r = -0.18$ $p = .188$
Rach-to-needle deceleration interval duration (ms)	193 ± 28	$r = -0.07$ $p = .598$	$r = -0.01$ $p = .925$

(p-values highlighted in bold are statistically significant at alpha level < 0.05)

(2,54) = 4.96, $p = .011$). Specifically, negative fusional vergence explained 8% of variance ($\beta = 0.39$, $p = .006$), and vergence facility explained 7% of variance ($\beta = 0.31$, $p = .025$) in peak reach velocity. For example, using the estimates from our regression analysis, results show that children with vergence facility > 14 cpm had peak reach velocity of 0.914 m/s, and children with lower vergence facility had peak reach velocity of 0.866 m/s. The VIF value for each predictor was less than 1.5, which indicates that risk of collinearity was low.

3.3.3. Accommodation

Accommodation and age were associated with a shorter total movement time ($R^2 = 0.31$, F(3,53) = 7.75, $p < .001$), and placement duration ($R^2 = 0.40$, F(3,53) = 11.83, $p < .001$). Specifically, it was found that accommodation explained 10% of variance in total movement time (binocular accommodative facility: $\beta = -0.30$, $p = .01$; amplitude of accommodation: $\beta = 0.24$, $p = .05$), and 13% of variance in placement duration (binocular accommodative facility: $\beta = -0.30$, $p = .01$; amplitude of accommodation: $\beta = 0.33$, $p < .01$). Age explained 21% of variance in total movement time ($\beta = -0.38$, $p = .002$), and 27% of variance placement duration ($\beta = -0.45$, $p < .001$). For example, using the estimates from our regression analysis, placement duration is 458 ms for a 10-year old child with BAF of 15 cpm, and for a child with a BAF of 5 cpm, the placement duration is 624 ms. VIF value for each predictor was less than 1.5, which indicates that risk of collinearity was low among these predictors. There were no significant predictors for reach duration, or for the duration of the reach acceleration interval or the reach deceleration interval ($p > .05$).

4. Discussion

The aim of this study was to assess the contribution of different aspects of binocular vision to the performance of a precision grasping and placement task in typically developing children ages 8–14 years with normal binocular vision. A bead threading task was used because it affords insight into the control of different movement components, such as reaching, grasping and placement. In addition, previous studies have shown a significant binocular advantage for the performance of bead threading in children and adults (Alramis et al., 2016; Gonzalez & Niechwiej-Szwedo, 2016). The main findings from this study indicate that horizontal fusional vergence and vergence facility were associated with higher peak velocity, stereoacuity was associated with shorter grasp execution, and amplitude of accommodation and binocular accommodative facility were associated with shorter placement duration.

To our knowledge, the current study is the first to show that vergence and stereopsis are associated with the control of distinct phases of a prehension movement in typically developing children. While it is well known that binocular viewing confers an advantage for the performance of prehension tasks (Melmoth & Grant, 2006), only few studies with adults used prisms and lenses to alter vergence eye movements or stereopsis (Melmoth et al., 2007; Mon-Williams & Dijkerman, 1999; Tresilian, Mon-Williams, & Kelly, 1999), and showed that these perturbations affect different phases of upper limb movements: reach and grasp, respectively. Our results are consistent with previous studies conducted with adults, and demonstrate these findings extend to the pediatric population. Importantly, our study did not involve any visual perturbations, testing was conducted during binocular viewing, and all children had normal visual acuity and stereoacuity. Therefore, our research suggests that the proficiency of motor skill performance is significantly dependent on the efficiency of binocular vision in typically developing children.

Results from the current study showed that lower stereoacuity thresholds are associated with more efficient grasp performance. Despite the relatively low range of stereoacuity thresholds in the current cohort, our results demonstrate that better stereoacuity confers an advantage for grasp execution. Specifically, children with stereoacuity of 20 arc secs performed the grasping task 80 ms faster on average compared to children with stereoacuity greater than 40 arc secs. It is important to consider that 20 arc secs was the lowest threshold that could be measured using the Randot® Stereoacuity test; however, it is possible that some children had thresholds that were lower than 20 arc secs. Although we are not aware of any studies that have measured stereoacuity thresholds beyond 20 arc secs in children, studies with adults have shown stereoacuity may be as low as 6 arc secs (Hess et al., 2016).

Fine stereopsis may provide important input for programming grip aperture and grasp forces. Disparity sensitive neurons are found in many regions of the parietal cortex, including the anterior intraparietal (AIP) area, which contains neurons that respond selectively to shapes defined by disparity (Theys, Srivastava, van Loon, Goffin, & Janssen, 2011). Encoding of shape information is critical for grasp planning and execution, thus, it is possible that a lower stereoacuity threshold allows a more precise encoding of the object's shape, which in turn would lead to a more precise positioning of the index finger and thumb, and subsequent force application that is precisely scaled to the material properties of the object. Extensive research shows that grasp forces are generated predictively based on visual input (Gordon, Forssberg, Johansson, & Westling, 1991); therefore, stereopsis could be contributing to this process. Adults and children with abnormal stereopsis have a prolonged grasp application (Grant et al., 2007; Suttle et al., 2011), suggesting that predictive control of grasping is compromised. In this case, the central nervous system must rely on haptic feedback and grasp duration is longer. Whereas previous studies showed that grasp execution is poorer in people with impaired stereopsis, our study is the first to show that grasp performance in typically developing children is influenced by stereoacuity thresholds in the normal range.

Results from the current study did not show a significant association between stereoacuity and peak reach velocity or duration of deceleration interval, which is in contrast to a previous study with a large cohort of children (Niechwiej-Szwedo et al., 2020). These results can be reconciled by considering the strength of the association. The correlation coefficient for stereopsis and peak velocity found in the previous study was -0.22, whereas the correlation in the current study was -0.13, which falls within the 95% confidence interval previously reported $[-0.35, -0.07]$. Therefore, results from both studies suggest that stereoacuity is weakly correlated with reach efficiency. The larger correlation found previously could be due to including children with a wider range of stereoacuities.

A novel finding in the current study is the association between vergence function and peak reach velocity. Horizontal fusional vergence refers to eye movements performed to focus on objects at different depths and maintain single binocular vision, and the muscular effort associated with a particular angle of either convergence or divergence can be used to extract the absolute location of the object in depth. (Howard & Rogers, 2002; Wilcox & Allison, 2009). Encoding an object's location in depth is critical for the performance of reaching movements. Peak reach velocity is scaled precisely with object distance, and higher peak velocity towards an object at a given distance is associated with shorter reach duration (Carey, Dijkerman, & Milner, 1998; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991), which reflects a more efficient reach execution. Our results suggest that better vergence function is associated with more efficient reach execution, and specifically higher peak reach velocity.

Consistent with previous work (Niechwiej-Szwedo, Alramis, & Christian, 2017) N, results from the current study showed that accommodation predicts a significant amount of variance in bead threading performance, and specifically, placement of the bead on a needle. Two previous studies noted that accommodation was correlated with motor skill performance in children diagnosed with a developmental coordination disorder (Rafique & Northway, 2015) and poor reading ability (Niechwiej-Szwedo, Alramis, & Christian, 2017). The current study used a kinematic approach to assess motor performance, thus, our results provide additional insight into which phase of the movement sequence presents the greatest challenge for the accommodative system, which is the placement task. Placing the bead on the needle requires a significant amount of accommodation and vergence because the needle is only 15 cm in front of the participant. The accommodative and vergence systems are neurally coupled, and function together to maintain single clear binocular vision. Thus, the lack of significant contribution of vergence to the performance of the placement task is difficult to explain.

Development of stereopsis and fusional vergence depends on post-natal visual experience (Braddick & Atkinson, 2011; Daw, 2006). Both functions emerge between two to three months after birth, but the maturation continues over the next decade, and possibly into the decade after. The current study used well established and standardized clinical measures to assess stereopsis, vergence, and accommodation; therefore, the results from our cohort can be compared with normative data. On average, children in the current study performed within the expected range on all tests (Scheiman & Wick, 2008), with the exception of the binocular accommodative facility (BAF), which was higher in our cohort. It is possible that the higher values in our study might be due to the fact that our sample included older children. However, this cannot fully explain our results because the association between age and BAF in our cohort was moderate (i.e., $r = 0.23$), and did not reach statistical significance. Age was not significantly associated with the clinical measures of binocular vision, except for vergence facility, which was moderately but significantly associated with age, and this finding is consistent with previous studies (Hussaindeen et al., 2017). It is important to acknowledge that the clinical tests measured only some aspects of binocular vision, and they generally show maturation before the age of 10 years. The results of these tests are used to make clinical diagnosis and plan appropriate treatments; however, more detailed measures of stereopsis and vergence might explain additional variance in visuomotor performance. For example, clinical tests assess stereoacuity thresholds over a limited range, and the lowest measurable threshold is 20 s of arc for the Randot® Stereoacuity Test. Thus, these tests have a ceiling effect because the exact thresholds might be lower than the values measured (O'Connor & Tidbury, 2018). Psychophysical approaches could be used to provide more a accurate and precise measurement of stereoscopic function (Giaschi et al., 2013). Similarly, clinical tests of horizontal fusional vergence use prism bars in free space, and rely on subjective responses to quantify performance. Detailed and objective measures of vergence eye movements could be obtained using eye tracking, and it remains to be established if such measures provide additional insight into the development and performance of fine motor skills.

To summarize, motor performance proficiency is associated with the efficiency of binocular sensory and motor function in typically developing children. In other words, children with better binocular vision tend to perform the task more quickly and accurately. Importantly, our study revealed that fusional vergence, stereopsis, and accommodation provide inputs to guide distinct phases of the movement: reaching, precision grasping, and placement, respectively. These findings have implications when considering the effects of visual and oculomotor impairments on upper limb movement control. For example, children diagnosed with poor vergence control might have less efficient control of reach execution, likewise, current literature shows that children with reduced stereopsis experience more difficulty with grasping (Grant, Suttle, Melmoth, Conway, & Sloper, 2014a; Suttle et al., 2011). Given the association between vergence and reaching, and stereopsis and grasping, it is important to consider whether training vergence and stereopsis could lead to improved motor performance. Conversely, an equally intriguing question is whether training aimed at improving proficiency of reaching or grasping would have any effects on vergence or stereopsis.

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Declaration of Competing Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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