Evaluation of Visual Function, Eye-Hand Coordination and Motor Ability in Typically Developing Children

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

Many aspects of a child's development contribute to thriving in everyday activities. For example, motor ability and visual function play a crucial role impacting social, physical and emotional development. While it is expected that better visual function would be associated with better motor performance, this association has not been directly assessed in school-aged, typically developing children. Thus, this study aims to characterize the visual function, motor ability, and hand-eye coordination in a typically developing cohort of children and to determine if there is any association between measures of visual function and motor performance.

A cohort of 35 children aged 7-14 years (9.7 SD 2.1 years, 19 males) were tested during a one-time visit which included three standardized clinical tests, an assessment of vision and binocular function, and an experimental hand-eye coordination task. The clinical tests consisted of the Movement Assessment Battery for Children (MABC-2) to assess overall motor development with subtests including fine and gross motor skills, the Beery Butkenica Developmental Test of Visual-Motor Integration (Beery-VMI) to assess visuomotor integration, and the Test of Word Reading Efficiency – 2nd Edition (TOWRE-2) to assess reading and pronunciation ability. The optometric assessment included visual acuity, stereoacuity, fixation disparity, phoria, fusional vergence, vergence facility, accommodative facility, and amplitude of accommodation. Eye-hand coordination was assessed using eye tracking and hand motion tracking while children performed a bead threading task.

Results from the optometric tests fell within expected ranges with the exception of vergence facility (13.5 SD 3.9) and binocular accommodative facility (9.2 SD 3.1). Performance on the TOWRE-2 subtests and the Beery-VMI aligned with the expected norms as well. The overall score for the MABC-2 was within the expected range (8.9 SD 2.1), however the manual dexterity subtest fell below the expected range (7.8 SD 2.8). A correlation analysis was performed revealing a relationship between the total MABC-2 score and vergence facility (ρ = -0.38, p = 0.04, 95% CI -0.65, -0.02) as well as accommodative facility (r = -0.48, p = 0.007, 95% CI -0.71, -0.05). The MABC-2 manual dexterity subtest score was associated with accommodative facility (r = -0.38 p = 0.037, 95% CI -0.71, -0.05). In addition, the amplitude of accommodation was associated with three kinematic measures from the bead threading task: the grasping interval (ρ = 0.63, p = <.001, 95% CI 0.35, 0.81), bead threading interval (ρ = 0.38, p = 0.041, 95% CI 0.02, 0.65), and total movement time (ρ = 0.42, p = 0.021, 95% CI 0.07, 0.67).

The findings from this study provide preliminary information about visual and motor function measures obtained from the same cohort of typically developing children. In contrast to the hypothesis, a negative moderate association was found between the MABC scores and accommodative and vergence facility. Similarly, the association between accommodation amplitude and bead threading task measures was in the opposite direction to the hypothesis. A larger study is necessary to determine whether the associations found in this small cohort are reliable. An important contribution of this study is the creation of a normative database that includes both the visual and motor scores. These normative values will be used when comparing the performance of children with a coordination disorder in a subsequent study.

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List of Abbreviations

VA: visual acuity

MAR: Minimum angle of resolution

BSV: Binocular single vision

CPM: Cycles per minute

CNS: Central nervous system

MABC-2: Movement Assessment Battery for Children – 2nd Edition

MD: Manual dexterity

AC: Aiming and catching

BT: Balance tasks

DCD: Developmental coordination disorder

ASD: Autism spectrum disorder

ADHD: Attention deficit hyperactive disorder

AB2: Age band 2

AB3: Age band 3

Beery-VMI: Beery-Buktenica Developmental Test of Visuomotor Integration

TOWRE-2: The Test of Word Reading Efficiency – 2nd Edition

IQR: Interquartile range

NVEb: Binocular acuity at 0.4m

Stereo: Stereoacuity

VF: Vergence facility

MAF: Monocular accommodative facility

BAF: binocular accommodative facility

MAoA: Monocular amplitude of accommodation

NFVbrk: Negative fusional vergence break point

PFVbrk: Positive fusional vergence break point

DCDq: Developmental coordination disorder questionnaire

MABC-T: MABC-2 total score

EHLat1: Eye-hand latency move 1

EHlat2: Eye-hand latency move 2

1.0 Introduction

Visuomotor function is important for performing most everyday activities, for example, reaching for a cup or driving. Being able to accurately represent an environment and act on visual input to guide and refine movements can impact many aspects of life. Visuomotor function relies on the integration of the visual inputs with the motor systems, to carry out goal-directed actions.

During the early years of life, children are learning and developing many fine and gross motor skills such as writing or riding a bike. Vision provides an important sensory input for learning and performing these skills. The development of the visual and motor systems occurs in parallel and over the course of childhood and into early adolescence. A deeper understanding of normal, or typical development will help to create better assessments for children with neurodevelopmental disorders. This is important because difficulties in visuomotor function can have consequences in multiple domains of life such as academic, physical, and social. Furthermore, there are many neurodisabilities that present with deficits in visuomotor function. Thus, it is important to understand the maturation and interaction between visual functions and motor skill performance to help further understand mechanisms behind neurodisabilities and their impact on developing children. The overarching goal of this study is to investigate the interaction between binocular vision functions and motor skill development through examining vergence and accommodative functions, motor skills, and hand-eye coordination of typically developing, school-aged children.

1.1 Visual Function and Processing

1.1.1 Overview of Visual Functions

Visual functions play a crucial role in sensorimotor control of goal directed actions. Some basic visual functions that can be assessed through routine optometric exams include visual acuity, stereoacuity, vergence, accommodation, fixation disparity and phoria.

Visual acuity (VA) is the measure of a minimum detectable difference between two points, a spatial resolving capacity of the visual system that has an important role in how the outside world is reflected onto the retina (Ikeda, 1979; Westheimer, 1965). VA is measured at near (0.4M) and far (6M) distances. There are various ways to measure VA, typically consisting of a chart of letters in rows that get incrementally smaller. As the letters get smaller, so do the spaces between them, allowing for the universal scoring of acuity consisting of determining the minimum angle of resolution (MAR). The MAR is the smallest angle between two points that can be resolved. VA notation can be expressed as a fraction, decimal or logMAR. Typical vision is 20/20 (Snellen notation) or 1.0 (decimal notation). When converted to logMAR, 20/20 vision is expressed as 0.00 logMAR, which is typically used for statistical analyses of acuity.

Stereopsis is the ability to see depth in the environment based on the inputs from the two eyes. When using both eyes to see the environment, there is a slightly different picture represented on both of the retinas (i.e., binocular retinal disparity), which provides relative depth information. The ability to see depth from binocular disparities is important for everyday interactions with our surroundings (Morris et al., 2005). The Randot® stereoacuity test is the most commonly used test in North America, as is appropriate for adult and pediatric patients. Stereopsis, quantified by the measure of stereoacuity is expressed in seconds of arc (arc sec),

indicating the difference in the angle between two points as they are reflected onto the two retinas. Similarly to visual acuity, it is measured as the smallest angle that can be detected. An expected typical result is <40 arc sec in typically developed adults (Birch et al., 2008).

Vergence is the ability to move the eyes in the opposite direction to maintain single binocular vision: towards the nose in order to converge on a nearer object or to turn the eyes outwards to diverge when looking at objects in the distance (Sinha, 2021). In clinical settings, vergence is tested through positive and negative fusional vergence and vergence facility. Both tests examine the dynamic abilities to move the eyes in response to the stimulus. For example, using a base-out prism (positive fusional vergence) induces convergence whereas a base-in prism (negative fusional vergence) induces divergence. Fusional reserves increase the demand on the vergence system such that the patient has to exert more effort to maintain single binocular vision. To measure fusional vergence, prisms of increasing value are used to increase the demand on the vergence system while the patient must maintain binocular single vision (BSV). Results are recorded as a blur point, the point where the patient loses comfortable BSV, break point, the point where the patient loses BSV, and recovery point, the point at which the patient regains BSV. Typical values for negative and positive fusional vergence are 12 ± 5 and 23 ± 8, respectively. Vergence facility is tested by alternating between base-out and base-in prisms to determine how many times the patient can converge and diverge in response to the stimulus in a one-minute interval. Vergence facility is measured in cycles per minute (cpm), with the average value in a typically developed visual system 16 ± 2.6 cpm.

Accommodation is neurally linked to vergence binocularly; however, it is tested separately with monocular viewing (Gamlin, 2002). Specifically, accommodation is the eye's ability to focus on a stimulus at different distances by changing the shape of the lens (Sinha, 2021) via

activation of the ciliary muscles. The amplitude of accommodation is measured in diopters, which measures the focusing ability of the lens. In short, diopters are the inverse of the focal length, which is the distance at which an object can come into focus, increasing in value and power as the focal length decreases (e.g., if focal length is close at 1/3 of a meter, the strength of the lens is 3 diopters [D]). Due to the decrease in accommodative ability throughout life, minimum value at an age is predicted through the equation; [D=15.0 - 0.25(age)] (Hofstetter, 1950), while average value at an age is predicted as [D=18.5-0.3(age)]. Additionally, accommodative facility, like vergence facility, is useful in the measurement of the dynamic capabilities of the system to relax or stimulate accommodation. The test consists of applying a +/- 2.00D lens to induce blur while reading a row of randomized letters. An expected typical value is 5±2.5cpm, with lower and more variable results being linked to myopia (Allen & O'Leary, 2006).

While it is not a formal function, fixation disparity and eye alignment are an important aspect of binocular vision. Fixation disparity is used to determine the alignment of the fixation point on the fovea during active binocular viewing, and phoria measures the misalignment of the eyes under dissociated viewing conditions. Fixation disparity occurs when the fused fixation point is not projected onto the center of the fovea in each eye (Jaschinski et al., 1999). This causes the visual axis from the two eyes to intersect either in front or behind the fixation point. Typically, this error does not lead to noticeable double vision. Phoria measures the latent deviation of the eyes in the absence of binocular viewing and characterizes the direction and magnitude of eye misalignment. Phoria and fixation disparity are reported using magnitude, measured in diopters, and direction, measured as eso for an inward deviation, exo for an outward deviation, hyper for upward, and hypo for downward deviations. Directional measures are used

to identify the direction that one or both the eyes is deviated, with respect to the other eye or fixation point. Expected values are 1exo ± 1 Δ for distance phoria and 3 exo ± 3 Δ for near phoria (Scheiman & Wick, 2008).

1.1.2 Vision Development in Typically Developing Children

Although infants are born with the ability to see, there is a critical period in which further development of the visual system takes place. During the first decade of life, the visual system further develops and refines based on visual experience. For example, newborn babies are able to perceive and react to visual stimuli, but visual acuity is adult-like at the age of approximately five years (Leat et al., 2009). Stereopsis emerges in infants at approximately 12-16 weeks of age (E. E. Birch et al., 1982) and continues to mature throughout the first decade of life (Afsari et al., 2013). In children, vergence ability is evident at approximately 3 weeks postnatally (Aslin, 1977; Bharadwaj & Candy, 2008). Performance matures to a point comparable to adults at approximately 4 years of age for vergence peak velocity, gain and duration of vergence movements (Yang & Kapoula, 2004), and 10-12 years for latency of vergence response (Yang et al., 2002). Similarly, accommodation is present at approximately 3 months of age with performance reaching adult levels at 7-10 years of age (Bharadwaj & Candy, 2008).

1.2 Overview of Motor Control

Movement production and fine motor skills are essential in everyday life, allowing humans to interact with their surrounding environment. Throughout the early years of life, it is important for children to have an opportunity to learn and refine motor skills. Fine motor skills may impact functional and educational domains and the importance of proper development cannot be understated (Chappell & Steitz, 1993).

Broadly speaking, motor control involves two main processes: motor planning and movement execution; however, there are multiple processes that contribute to fast, accurate and precise performance (Elliott et al., 2017). An important aspect of movement planning and execution has been studied in the context of the internal modelling hypothesis, which explains how movements are optimized and learned. Internal modelling is the hypothesis that the central nervous system (CNS) uses predicted and actual sensory feedback of a movement to carry out a motor behaviour. The importance of internal modelling comes into play when the relative delay of actual sensory information is considered. While using sensory (afferent) feedback is a crucial aspect for correcting movements, it is relatively slow, thus, the system relies on internal modelling of the movement dynamics to predict the sensory consequences, which can be compared with the actual sensory feedback. Internal modelling is often divided into two main mechanisms: forward and inverse internal models (Wolpert & Ghahramani, 2000). The forward internal model is used to predict the consequences of the desired action while the inverse internal model uses the desired consequences to generate a motor command for the action. Internal modelling facilitates motor learning to improve the motor commands and efficiency of using appropriate feedback, thus, allowing seamless control of movements.

1.2.1 Development of Motor Control

Like the visual system, infants are born with the capacity to respond reflexively and might be capable of making rudimentary movements a few weeks after birth, but the motor system undergoes a protracted maturation process extending into the second decade of life. Studies have shown that before the age of seven years, children typically perform ballistic movements mainly relying on feedforward control, and do not use online feedback during movement execution to correct movements. In middle childhood, children begin to incorporate

visual feedback to make trajectory corrections as they execute movements. Optimizing the interaction between feedforward and feedback control takes a long time to mature such that progressing to adult level performance becomes evident after the age of 10 years (Hay et al., 1991; Schneiberg et al., 2002). This shift in the control strategy allows for increased efficiency and effectiveness in motor skill performance.

1.2.2 Evaluation of Motor Development

Motor development is encouraged in social and educational environments through various tasks. There are many tests that can be used to measure the progress of motor skill development throughout childhood. The Movement Assessment Battery for Children – 2nd Edition (MABC-2) is one of the most utilized tools in North America. The MABC-2 consists of three subtest sections to help capture progress in both fine and gross motor abilities. The subtests cover manual dexterity (MD), aiming and catching (AC) and balance tasks (BT). Together all three subtests are scored according to age standardized scales to produce an overall score. A percentile score of 15 or lower identifies a child at risk of motor difficulties and a percentile score below 5 identifies a child likely having motor difficulty (Henderson et al., 2019). The MABC-2 is often used as an aid in diagnosing developmental coordination disorder (DCD). While the MABC-2 provides a comprehensive overview of a child's current motor developmental progress, it is time consuming to administer and does not provide insight regarding the underlying sensorimotor problem contributing to poor performance.

1.3 Visuomotor Control and Development

Experimental studies that used motion tracking and assessed limb kinematics provide insight into the development of sensorimotor control (van der Meer, 1997; von Hofsten, 1982; von Hofsten & Fazel-Zandy, 1984). As an example, van de Meer (1997) probed the ability of

newborn babies to use vision to control their limbs with results showing limb movements towards targets, establishing precursors to eye-hand coordination. As infants progress through childhood, their movement strategies gradually develop into refined movement patterns that eventually resemble adult like performance. Typically, before the age of seven years, children perform a ballistic movement pattern when reaching (Hay, 1979). Between the ages of seven and ten years, children start to develop the capability to use visual feedback during movement execution, paradoxically, their movements become slower but tend to be more precise (Smyth et al., 2004). From the experiment carried out by Smyth et al. (2004), when vision was removed during a prehension movement, the younger group of children (5-6 year-olds) showed no change to movement time or peak velocity, whereas the older children (9-10 year-olds) executed slower movements. These results suggest in the older group of children, the system may be using visual input during movement for online control. Once children reach the age of 10 years, there is much more evidence towards an effective use of visual information and visuomotor integration ability. In addition to the previously mentioned impact of eliminating visual input a study by Contreas-Visal et al (2004) demonstrated aftereffects in older children for a visuomotor task suggesting a further developed internal visuomotor representation of hand movements. Finally, a large study evaluating the kinematic performance using a prehension task showed a plateau in performance at the approximate age of 10.5 years in measures such as total movement time, grasp, placement and reaching durations (Niechwiej-Szwedo, Meier, et al., 2020). Thus, children's motor control system becomes more adult-like after the age of 10 years; however, it is likely that maturation and fine-tuning continues into adolescence.

Hand-eye coordination is an important aspect of visuomotor control. The coupling of eye and hand movements has been evaluated using the eye-hand latency difference. Studies

demonstrate a consistent pattern where an initial eye movement to a target is followed by the hand with a latency of ~150ms. Multiple studies have shown this relationship between saccades and hand movement (Brouwer et al., 2021; Sailer et al., 2000). This coupling allows for important visual information to be used for the planning and execution of an accurate movement. Fixating on the target increases reach accuracy through multiple mechanisms, foveal input to encode the target location and peripheral visual feedback of limb trajectory (Prablanc et al., 1979). Eye-hand coordination has been examined in a study with typically developing children using a bead threading task. This task involves a four-movement sequence of reaching to the bead, grasping it, returning the bead to the needle, and accurately threading the bead onto the needle. This sequence allowed for the evaluation of two eye-hand latency for two segments: 1) in response to an auditory cue which was used to initiate a reaching movement, and 2) after grasping the bead when the gaze and eyes moved towards the needle. In the cohort of 60 children, the younger group (<11 years old) showed larger initial eye hand latency difference, and a lag in eye movement when returning to the needle after grasping the bead. In contrast, the older children (>11 years old) showed eye-hand latency times comparable to adults (Niechwiej-Szwedo et al., 2021). These results suggest the aspects of eye-hand coordination continue to mature into adolescence.

To summarize, the first decade of a child's life is a critical developmental period for visuomotor control. It is important to understand how the sensory and motor systems develop independently and work together to optimize learning spaces and opportunities for children to thrive. A better understanding of typical development will provide a foundation to create targeted assessment tools and treatments to help identify neurodevelopmental disorders.

Technology such as motion tracking and eye tracking has been used to develop a better understanding of visuomotor development in experimental lab settings. With recent advances in portable technology, these assessments could be performed outside of the typical laboratory and instead implemented in clinical or educational settings. However, there are challenges that need to be addressed. One important area for investigation is to develop a set of tasks and measures that could be used to assess visuomotor development using technology. On the other hand, given the importance of visual input for motor control, a better understanding about the interaction between vision function and visuomotor control is also required. For example, if a child is having trouble grasping their hairbrush it could be due to inaccurate visual input or inaccurate integration of vision and somatosensory inputs, a problem with sensorimotor transformation or movement execution. It is not possible to discern the root of the problem using the current standardized tools such as MABC-2. Thus, developing novel tools and approaches to address this is important.

Rationale for Study

Vision is crucial for planning and executing accurate goal directed motor actions. There is a dearth of studies that investigated the association between visual functions and visuomotor control in the same group of children. Thus, the aim of the current study was to characterize the association between visual functions, fine motor skill and visuomotor coordination concurrently in typically developing school-aged children.

Research Question

Is lower visual function associated with poorer fine motor skills and hand-eye coordination profiles?

Hypothesis

It was hypothesized that there will be a relationship between visual function and hand-eye coordination profiles, specifically, children with better vision will perform fine motor skills faster and with a higher accuracy.

2.0 Methods

2.1 Participants

Typically developing children aged 7-14 years old were recruited through the participant database accessed through the Waterloo Eye Institute at the University of Waterloo. Children were excluded if they had any pre-existing neurodevelopmental disorder, such as diagnosed autism spectrum disorder (ASD), attention deficit hyperactive disorder (ADHD). Other exclusions include amblyopia, strabismus, ocular disease (i.e. congenital cataract), or were classified as pre-term (<37 weeks gestational age). The cohort included 35 children (mean age 9.74 yrs ± 2.05; 16 girls, 19 boys). Participants were further stratified into two age groups, the younger group consisting of 25 children aged 7-10 years (mean age 8.68 ± 1.12; 13 girls, 12 boys), and the older group consisting of 10 children aged 11-14 years (mean age 12.4 ± 1.27; 3 girls, 7 boys). This age stratification is aligned with previous studies (Henderson et al., 2019; Niechwiej-Szwedo, Meier, et al., 2020).

2.2 Experimental Protocol

Data collection involved a single two-hour session in the Developmental Visuomotor Neuroscience lab at the University of Waterloo. Parental consent and child assent were obtained prior to the collection. Children completed four clinical tests and three experimental tasks, and their parents completed one questionnaire. This study was approved by the Research Ethics Board of the University of Waterloo (ORE #44844).

2.2.1 Optometric Assessment

All visual function assessments were performed by a registered optometrist or qualified optometry student at the University of Waterloo School of Optometry and Vision Science. A

battery of visual assessments is described in Table 1. Visual acuity was evaluated at near (0.4M) and far (6M) distances. Stereoacuity was assessed at gross and local levels. Both fixation disparity and eye alignment were evaluated. Accommodative facility was evaluated monocularly and binocularly while amplitude of accommodation, vergence facility and negative and positive fusional vergence were evaluated monocularly.

Table 1. Description of visual assessments

Test Name	Visual Test	Expected
Bailey Lovie Chart	Visual Acuity – Distance – 6M (logMAR)	0.00
Reduced Snellen	Visual Acuity – Near – 0.4M (logMAR)	0.00
Randot®	Stereoacuity – gross and local (arcsec)	250 (Global) 40 (Local)
12BO/3BI Prism	Vergence Facility (cycles/min)	15±3cpm
Saladin Card	Phoria (Diopters)	Distance: 1Exo Near: 3Exo
Rock Card (+/- 2.00D)	Accommodative Facility (Cycles/min)	5.0 ± 2.5cpm (Binocular) 7.0 ± 2.5cpm (Monocular)
RAF ruler	Amplitude of Accommodation (Diopters)	18-1/3age
Prism bar	Fusional Vergence – negative and positive Blur/break/recovery (Diopters)	12 ± 5 (break negative) 23 ± 8 (break positive)

2.2.2 Movement Assessment Test

Children completed the Movement Assessment Battery for Children – Second Edition (MABC-2), a standardized movement assessment evaluating skills in three domains including manual

dexterity (three tasks), aiming and catching (two tasks), and balance (three tasks). The MABC-2 tasks vary depending on the child's age, stratified into three age bands. The current study included age band two (AB2: 7 – 10 years old) and age band three (AB3: 11 -16 years old). Detailed description of each task for both age bands is shown in Table 2.

Table 2. Description of motor tasks included in two age bands

	AB2	AB3
Manual Dexterity 1	Place pegs into a peg board	Turning pegs in a peg board
Manual Dexterity 2	Threading lace in proper pattern	Copy a shape with nuts and bolts
Manual Dexterity 3	Follow a drawing trail, inside the lines with no mistakes	Follow a drawing trail, inside the lines with no mistakes
Aiming & Catching 1	Catching a ball with two hands	Catching a ball with one hand
Aiming & Catching 2	Throwing a beanbag onto a mat with a target	Throwing at a wall target
Balance 1	Amount of time spent balancing on a balance board	Amount of time spent balancing on a balance board
Balance 2	Walking heel-to-toe forward	Walking heel-to-toe backwards
Balance 3	Hopping on mats in a straight line	Zig-zag hopping on mats

Performance on each task was evaluated based on timing and/or accuracy following the guidelines in the manual (Henderson et al., 1992). Raw scores were then converted to a scaled score ranging between 1 and 19, which were standardized based on the age of the participant. Next, scaled scores were summed to produce the component score for each subsection of the

MABC-2. The component scores were summed to produce the total score, which were converted to standardized scores ranging between 0 and 19, and percentile scores ranging between 1 and 100. According to the testing manual, percentiles are classified into three categories. Any participant scoring above the 15th percentile is considered not at risk for movement disorders. Participants scoring between the 5th and 15th percentile are considered at risk for a movement disorder. Participants scoring below the 5th percentile is flagged and considered to have a movement disorder. Scaled and standardized scores were used for statistical analysis in the current study.

2.2.3 Beery-Buktenica Developmental Test of Visuomotor Integration

The Beery-Buktenica Developmental Test of Visuomotor Integration (Beery-VMI) is used to assess the integration of visual perception and motor behavior (Beery, 1989). The test consists of 24 geometric figures that the child is asked to copy, which gradually increase in difficulty**.** If the participant makes three mistakes in a row or scores below a threshold on the main test, they are required to complete two additional subtests. The subtests focus on tasks involving visual perception and motor ability separately in order to ascertain where the difficulties may originate. Overall scaled scores are expected to fall between 90 –110 for typically developing children. Any scores above 110 or below 90 are considering above or below average performance, respectively. Every test is scored immediately to determine whether or not progression to the additional subtests is required. Scoring is done based on the drawings made by the participants. Some examples of criteria involved in the marking include the angle of a drawn line, how the shapes overlap or touch and the overall similarity with the model shape. The raw score is

converted to a scaled score, standardized score and a percentile rank, as well as an age matched score. Standardized scores were used in the evaluation of the results presented in this document.

2.2.4 Test of Word Reading Efficiency – Second Edition

The Test of Word Reading Efficiency – Second edition (TOWRE-2) was used to assess reading ability. The TOWRE-2 consists of two subtests that individually assess the ability to pronounce printed words – the sight word efficiency subtest – and phonemically regular nonwords – phonemic decoding efficiency subtest. Participants are first asked to read the six practice words. Then they begin the test which involves reading the words printed in columns. The score indicates the number of words articulated in 45 seconds. Performance on the test was audio recorded for analysis. When comparing scaled scores, a typically developing child is expected to fall within a range of 90 – 110. Any score above 110 is considered *above average* while scores below 90 are considered *below average.*

Using the test recording, each test is graded based on the number of words correctly read and pronounced. Using the number of correct words, the score was then converted to an age-equivalent, percentile rank, and scaled score for further comparison and analysis.

2.2.5 Experimental Task - Motor Skill Assessment

A bead threading task, shown in Figure 1, was used to assess eye-hand coordination and prehension kinematics. The task consists of four distinct components: reaching for a bead, grasping the bead, transporting it to the needle, and threading it onto a needle. The bead threading task was performed while children were seated at a table with their chin placed in a chinrest. The task apparatus and computer monitor were directly in front and aligned with the child's midline. Two infrared markers were attached on the thumb and index finger of the preferred hand, in a way not to impede or influence natural movement. The infrared markers

were used to record finger and thumb position via the Optotrack motion capture system (3D Investigator, NDI, Waterloo, ON). Sampling frequency was 250Hz. Eye tracking data were also recorded at 250Hz using the Eyelink II head-mounted, camera-based eye tracker (SR Research, Mississauga, Ontario, Canada). The eye tracker was set up to allow pupil tracking across the workspace prior to calibrating and validating the device with <1 degree of error during validation. Tracking was either binocular or monocular depending on the quality of the calibration (i.e. if both eyes validated <1 degree of error, both eyes would be tracked, if only one eye achieved <1 degree of error, only that eye was tracked). The apparatus was set up at participant's midline, with a computer screen placed 80 cm away from the chin rest. The bead was placed 35 cm from the chinrest, and the vertical needle was placed 15cm from the chinrest (Figure 1). Each trial began with the finger and thumb placement on the tip of the needle, an auditory signal was used as the 'GO' signal. Children were asked to perform the task as fast as possible without dropping the bead. Practice trials were performed to ensure children understood the task, which were followed by 15 experimental trials.

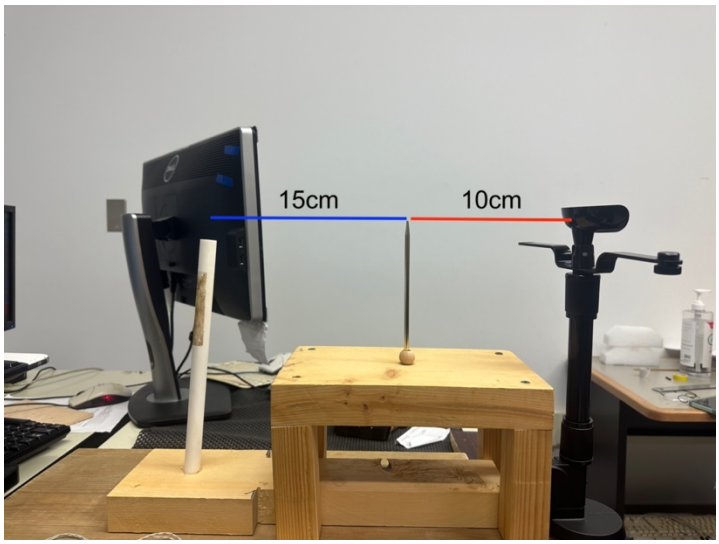


Figure 1. Setup for bead threading task.

2.3 Signal Processing

To evaluate eye-hand coordination, the hand and eye movement data were plotted and analyzed using a custom written Matlab script. First, the raw data were filtered using a second order, dual, low pass Butterworth filter with a cut off frequency of 10Hz for the finger/thumb data, and 80 Hz for the eye tracking data. Eye movement initiation was detected when the vertical or horizontal eye velocity exceeded 20deg/s. 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. All data were visually inspected to ensure the initiation and termination was identified correctly for each trial. Saccades associated with the reaching movements were manually selected and exported.

Each trial of the bead threading task consisted of four main movement phases: reach to bead, bead grasp, return to needle, and bead thread on the needle (Figure 2). Kinematic measures extracted were characterized using the four movement phases. Reaction time was measured as the initiation of the movement after the auditory Go signal, reach to bead duration was measured from movement initiation to termination using the velocity criteria described above. Bead grasp interval was measured as the duration between reach termination and when the reach to needle was initiated. The bead threading interval was measured as the interval from reach termination as the hand approached the needle to when the hand moved away from the needle (children were instructed to point away from the needle after threading the bead). Other kinematic measures also extracted included the time and magnitude of peak velocity when reaching to bead and needle.

Each participant completed 15 trials of the bead threading task. Once analyzed, only participants with a minimum 5 valid trials were included in further analysis. Two participants were excluded from all analysis because there were fewer than 5 usable trials due to missing marker data. Three participants were excluded from eye movement analysis due to loss of eye tracking signal, but kinematic data were still useable.

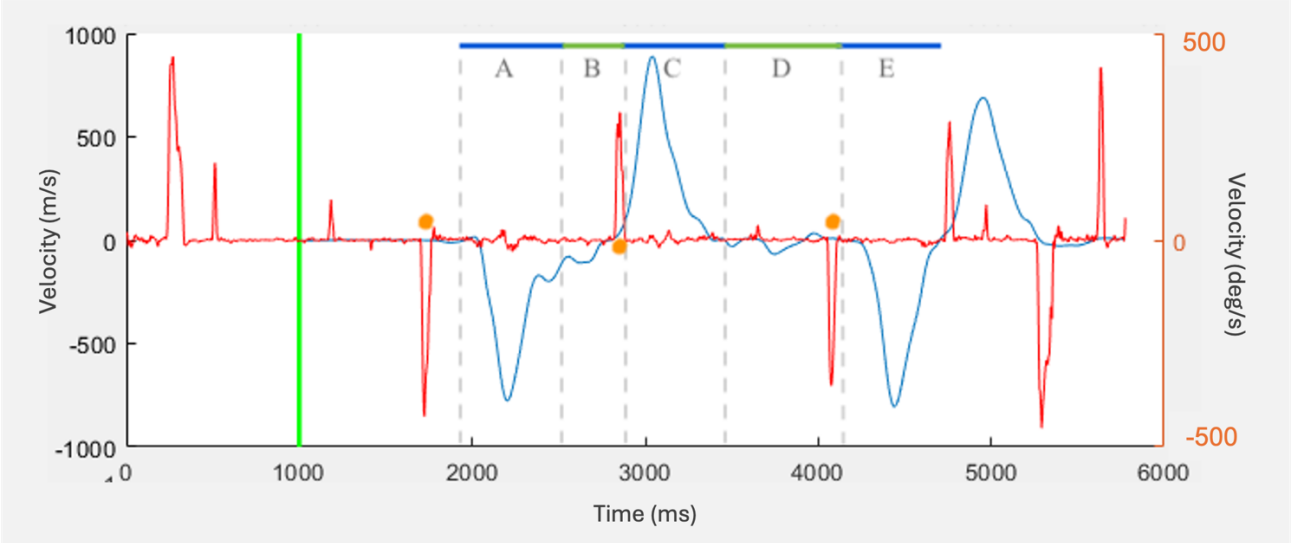


Figure 2. Example of eye (red) and hand (blue) velocity trajectories during bead threading task. Panels A: reach to bead; B: bead grasping; C: reach return to needle; D: bead threading; E: movement away from the needle indicating the end of task. Orange circles show the eye movements analyzed

2.4 Statistical Analysis

Statistical analyses were conducted using JASP open-source statistical analysis program (University of Amsterdam, Amsterdam, The Netherlands). All data underwent univariate analysis to assess for outliers and normality. Once outliers were identified using the interquartile range (IQR) criteria, they were flagged and then evaluated for physiological probability and removed if the values fell outside of the physiological range.

To assess the association between visual function and motor proficiency correlation coefficients were calculated between all clinical tests: motor (MABC-2), visuomotor integration (Beery-VMI), reading (TOWRE-2), and binocular vision assessment. When both measures were normal, Pearson's correlation coefficient (r) was used, whereas when one of the measures was not normal Spearman's correlation coefficient (ρ) was used. Second, children who scored <15% for MABC-2 were investigated in more detail to determine if any of the binocular vision assessments explain poor motor performance.

Similarly, a correlation analysis was preformed to investigate any association between the visual and kinematic outcome measures. Performance of the younger (AB-2) and older (AB-3) children on the bead threading task was compared using a Student's t-test when both measures were normally distributed, and the Mann-Whitney U-Test when one measure was not normally distributed. The significance level was set at $p<0.05$. A detailed graphical analysis was performed for the children at risk of movement difficulties to determine if the kinematic analysis could help to explain the deficits in motor skills.

3.0 Results

Table 3 provides a summary of the number of participants who completed the various tests and provided usable data for statistical analyses. The explanation for missing data is also provided in the table.

Table 3. Number of participants who completed each test (total cohort =35)

Test		Number of participants with usable data	Explanation for missing data
Visual Acuity	Distance	33	Unfinished testing
	Near	32	Recording error, unfinished testing
Stereoacuity	Gross	33	Unfinished testing
	Local	33	Unfinished testing
Vergence Facility		32	Two outliers removed; values recorded were outside of the physiological range
Amplitude of Accommodation	Left	32	Unfinished testing, unable to test
	Right	32	Unfinished testing, unable to test
Accommodative Facility	Monocular	33	Unfinished testing
	Binocular	26	Binocular accommodative facility was not assessed for 9 children due to an error
Fusional Vergence	Positive	32	Unfinished testing
	Negative	32	Unfinished testing, recording error
MABC-2		33	Unable to test
Beery		34	Unable to test
Reading Tests		30	Unable to test
Beads Experimental Task	Kinematic	33	Motion tracker signal incomplete
	Eye	30	Eye tracker signal error
DCDq		32	Incomplete surveys

3.1 Standardized Clinical Tests

The main objective of the clinical tests was to evaluate the participants' motor, visuomotor and reading capabilities, along with visual function in a standardized way. Results from the visual assessment are presented in Table 4. Acuity was within normal range at both distances of 6M and 0.4M during monocular and binocular viewing. Two children had stereoacuity equal to or greater than 40 arc sec (i.e., below expected normative value). Accommodation amplitude was below age expected minimum values in 21 children with 43% of the sample falling within one standard deviation of the expected mean, 48% within two standard deviations and 9% falling three or more standard deviations from the mean. Similarly, accommodative facility was below norms in four children during monocular testing (2.9 SD 1.7), and in one child during binocular testing (2.5 cpm). Finally, vergence facility was lower in 17 children (10.72 SD 1.8, range: 6.0 – 13.0) compared to the expected value of 16±2.6 cpm.

Table 4. Description of visual function measures

	NVEb (logMAR)	MAoA (diopters)	MAF (cycles/min)	BAF (cycles/min)	VF (cycles/min)	PFV (diopters)	NFV (diopters)
n	32	32	33	26	32	32	32
Mean (±SD)	-0.07 (±0.05)	12.00 (±3.00)	8.53 (±3.75)	9.19 (±3.13)	13.47 (±3.97)	21.84 (9.77)	16.25 (7.35)
Median	-0.10	11.25	7.75	9.50	12.75	19.00	16.00
Min	-0.10	6.00	0.50	2.50	6.00	6.00	6.00
Max	0.00	20	16.5	15.5	24	45.0	40.0
Expected	0.00	15.0 - 0.25(age)	7.0±2.5	5±2.5	15±3	23	12

Note. NVEb: binocular acuity at 0.4m; MAoA: monocular amplitude of accommodation; MAF: monocular accommodative facility; BAF: binocular accommodative facility; VF: vergence facility; NFV: negative fusional vergence; PFV: positive fusional vergence. All expected values noted as described by Schieman and Wick (2008), Gall, Wick & Bedell (1998), and Hofstetter (1950).

Table 5. Correlation between visual function measures. Bolded test indicates a significant correlation ($p<0.05$).

	NVEb	Stereo	MAoA	MAF	BAF	VF	PFVbrk
NVEb	1.0						
Stereo	ρ = -0.05 p = 0.773 n = 32	1.0					
MAoA	ρ = -0.22 p = 0.226 n = 31	**ρ = -0.40 p = 0.025 n = 32 CI = [-0.654, -0.054]**	1.0				
MAF	ρ = 0.12 p = 0.498 n = 32	ρ = 0.25 p = 0.170 n = 33	ρ = -0.05 p = 0.774 n = 32	1.0			
BAF	ρ = -0.08 p = 0.710 n = 25	ρ = 0.28 p = 0.160 n = 26	ρ = -0.15 p = 0.462 n = 25	**r = 0.61 p = <.001 n = 26 CI = [0.292, 0.807]**	1.0		
VF	ρ = 0.25 p = 0.173 n = 31	ρ = 0.09 p = 0.626 n = 32	ρ = -0.17 p = 0.363 n = 31	ρ = 0.20 p = 0.272 n = 32	**ρ = 0.59 p = 0.002 n = 25 CI = [0.248, 0.797]**	1.0	
PFVbrk	**ρ = -0.39 p = 0.030 n = 31 CI = [-0.655, -0.043]**	ρ = 0.07 p = 0.706 n = 32	ρ = 0.25 p = 0.165 n = 32	r = 0.19 p = 0.287 n = 32	r = 0.34 p = 0.09 n = 25	ρ = 0.22 p = 0.229 n =31	1.0
NFVbrk	ρ = -0.13 p = 0.478 n = 31	ρ = -0.27 p = 0.135 n = 32	ρ = -0.01 p = 0.942 n = 31	ρ = 0.10 p = 0.570 n = 32	ρ = 0.27 p = 0.190 n = 26	ρ = 0.09 p = 0.615 n = 31	ρ = 0.19 p = 0.307 n = 31

Note. NVEb: binocular acuity at 0.4m; Stereo: local stereoacuity; VF: vergence facility; MAF: monocular accommodative facility; BAF: binocular accommodative facility; MAoA: monocular amplitude of accommodation; NFVbrk: negative fusional vergence break point; PFVbrk: positive fusional vergence break point

As shown in Table 6, the Beery-VMI scores were within normal range, except for one child scoring 86. Similarly, five children scored slightly below age expected performance for the reading test in the sight word subtest (83.80 SD 4.82), and six children in the phonemic decoding subtest (84.83 SD 3.60).

Table 6. Descriptive statistics for the clinical test of visuomotor integration (Beery-VMI), reading (TOWRE-2: sight word and phonemic), and parental report of motor proficiency (DCDQ).

	Beery-VMI	TOWRE-2: Sight Word	TOWRE-2: Phonemic	DCDQ
n	34	30	30	32
Mean (SD)	111.3 (10.2)	104.3 (14.9)	103.1 (13.9)	67.7 (6.9)
Median	112.0	103.5	103.5	69.0
Min	86.0	79.0	79.0	54.0
Max	129.0	138.0	126.0	75.0

The parental report of motor coordination (i.e., DCDQ) is shown in Table 6. According to parental observation, four children were having difficulty in motor coordination. The MABC-2 test is typically used to support the clinical diagnosis of DCD. Results from MABC-2 are shown in Figure 3 and Table 7. Children scoring below the fifth percentile are typically identified as having probable DCD. In the current study, the poorest performance was found for the Manual Dexterity component where six children scored at or below the fifth percentile. For the Aiming and Catching component three children scored at or below the fifth percentile. In the case of the Balance test, one child scored at the fifth percentile. Based on the total score from the MABC-2 test, the cohort of children tested in the current study included four participants at risk for motor difficulties with one child with probable DCD. The current study focused on fine motor skills, thus, case studies were selected based on an evaluation of the manual dexterity subtest. There

were 8 children (23%) who scored at or below the 5th percentile. For further case study classification and evaluation see Section 3.3.

Table 7. Summary of MABC-2 standard scores.

	Manual Dexterity	Aiming and Catching	Balance	Total Score
n	33	33	33	33
Mean (±SD)	7.8 (±2.8)	9.4 (±2.9)	10.7 (±2.7)	8.9 (±2.1)
Median	8.0	9.0	11.0	9.0
Min	3.0	4.0	5.0	5.0
Max	13.0	18.0	15.0	15.0

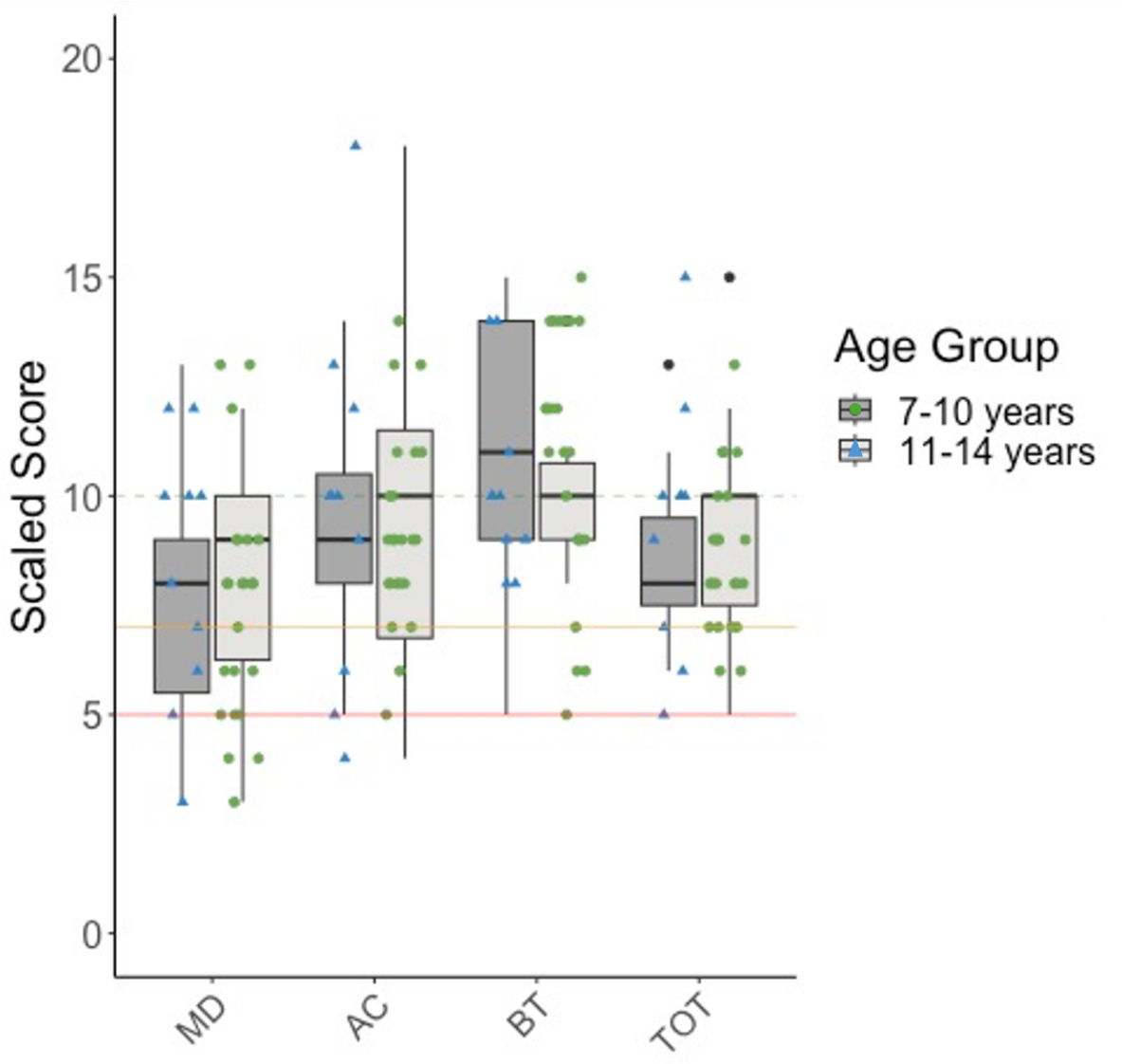


Figure 3. Boxplot with individual points to show the distribution of scaled scores obtained from the MABC-2 test, including Aiming & Catching (AC), Balance (BT), Manual Dexterity (MD), and Total (TOT) scores. Scores are stratified by age band: AB2 (7 – 10 years,) & AB-3 (11 – 14 years). Dashed green line represents expected score, solid yellow represents where scores are at risk and the solid red line represents poor motor ability.

Table 8. Correlation between visual function and clinical tests.

	MABC-T	MD	DCDq	Beery
MABC-T	1.0			
MD	*r* = 0.68 p = <.001 n = 33	1.0		
DCDq	ρ = 0.24 p = 0.296 n = 30	ρ = -0.06 p = 0.742 n = 30	1.0	
Beery	*r* = 0.15 p = 0.401 n = 33	*r* = -0.01 p = 0.960 n = 33	ρ = -0.09 p = 0.614 n = 31	1.0
nVEb	ρ = 0.08 p = 0.668 n = 30	ρ = -0.17 p = 0.358 n = 30	ρ = 0.08 p = 0.648 n = 29	ρ = 0.05 p = 0.799 n = 31
Stereo	ρ = -0.24 p = 0.200 n = 31	ρ = -0.20 p = 0.291 n = 31	ρ = 0.10 p = 0.606 n = 30	ρ = -0.34 p = 0.059 n = 32
VF	**ρ = -0.38** **p = 0.041** **n = 30**	ρ = -0.25 p = 0.183 n = 30	ρ = 0.01 p = 0.979 n = 29	ρ = -0.15 p = 0.429 n = 31
MAF	***r* = -0.48** **p = 0.007** **n = 31**	***r* = -0.38** **p = 0.037** **n = 31**	ρ = -0.02 p = 0.924 n = 30	*r* = 0.09 p = 0.609 n = 32
BAF	***r* = -0.43** **p = 0.031** **n = 25**	***r* = -0.44** **p = 0.028** **n = 25**	ρ = -0.02 p = 0.920 n = 24	*r* = 0.09 p = 0.656 n = 26
MAoA	ρ = -0.02 p = 0.911 n = 30	ρ = -0.08 p = 0.679 n =30	ρ = -0.02 p = 0.936 n = 29	ρ = 0.35 p = 0.056 n = 30
NFVbrk	ρ = -0.23 p = 0.226 n = 30	ρ = 0.02 p = 0.927 n = 30	ρ = -0.35 p = 0.061 n = 29	ρ = 0.25 p = 0.170 n = 31
PFVbrk	*r* = 0.02 p = 0.910 n = 30	*r* = -0.06 p = 0.757 n = 30	ρ = 0.21 p = 0.276 n = 29	*r* = 0.02 p = 0.907 n = 31

Note: MABC-T: MABC-2 total standard score; MD: manual dexterity subtest standard score; DCDq: Developmental Coordination Disorder Questionnaire score; Beery: Beery-VMI scaled score. See Table 5 for all vision measure abbreviations.

3.2 Bead-Threading Kinematic Results

The bead threading task was used to evaluate prehension kinematics and eye-hand coordination. The duration of reaching movements was similar across the age groups (Figure 4): reach to bead (AB2: 460ms SD 55; AB3: 471ms SD 61), reach to needle (AB2: 432ms SD 55; AB3: 428ms SD 32). In contrast, grasping was significantly longer (W = 61.0, p=0.034) for the younger group (AB2: 314ms SD 127) compared to the older group (AB3: 208ms SD 100); threading was also significantly longer (W= 59.0, p=0.028 for AB-2: 893ms SD 320 compared to AB-3: 674ms SD 283). Eye-hand latency (Figure 4) was not significantly different between the groups (p>0.05) for the reach to bead movement (AB2: 194ms SD 131; AB3: 284ms SD 149) or the reach to needle movement (AB2: 48ms SD 99; AB3: 46ms SD 8).

Table 9. Correlation between visual function and bead threading kinematic measures. Bolded values highlight the significant correlations.

	nVEB	Stereo	VF	MAF	BAF	MAoA	Nfvbrk	Pfvbrk
TMT	ρ = -0.05 p = 0.808 n = 30	ρ = -0.29 p = 0.115 n = 31	ρ = -0.12 p = 0.516 n = 30	*r* = 0.06 p = 0.755 n = 31	*r* = -0.11 p = 0.610 n = 25	**ρ = 0.42 p = 0.021 n =30 CI = [0.07, 0.67]**	ρ = 0.31 p = 0.096 n = 30	*r* = -0.04 p = 0.846 n = 30
GI	ρ = -0.13 p = 0.493 n = 30	ρ = -0.33 p = 0.072 n = 31	ρ = 0.02 p = 0.933 n = 30	*r* = -0.01 p = 0.955 n = 31	*r* = -0.04 p = 0.843 n = 25	**ρ = 0.63 p = <.001 n = 30 CI = [0.349, 0.807]**	**ρ = 0.37 p = 0.044 n = 30 CI = [0.012, 0.645]**	*r* = 0.11 p = 0.558 n = 30
BTI	ρ = -0.07 p = 0.708 n = 30	ρ = -0.17 p = 0.373 n = 31	ρ = -0.19 p = 0.318 n = 30	ρ = 0.07 p = 0.707 n = 31	ρ = -0.04 p = 0.859 n = 25	**ρ = 0.38 p = 0.041 n = 30 CI = [0.018, 0.648]**	ρ = 0.31 p = 0.098 n = 30	ρ = 0.08 p = 0.671 n = 30

Note: TMT: Total movement time of bead threading task; GI: grasping interval time; BTI: bead threading interval time. See table 5 for vision measure abbreviations.

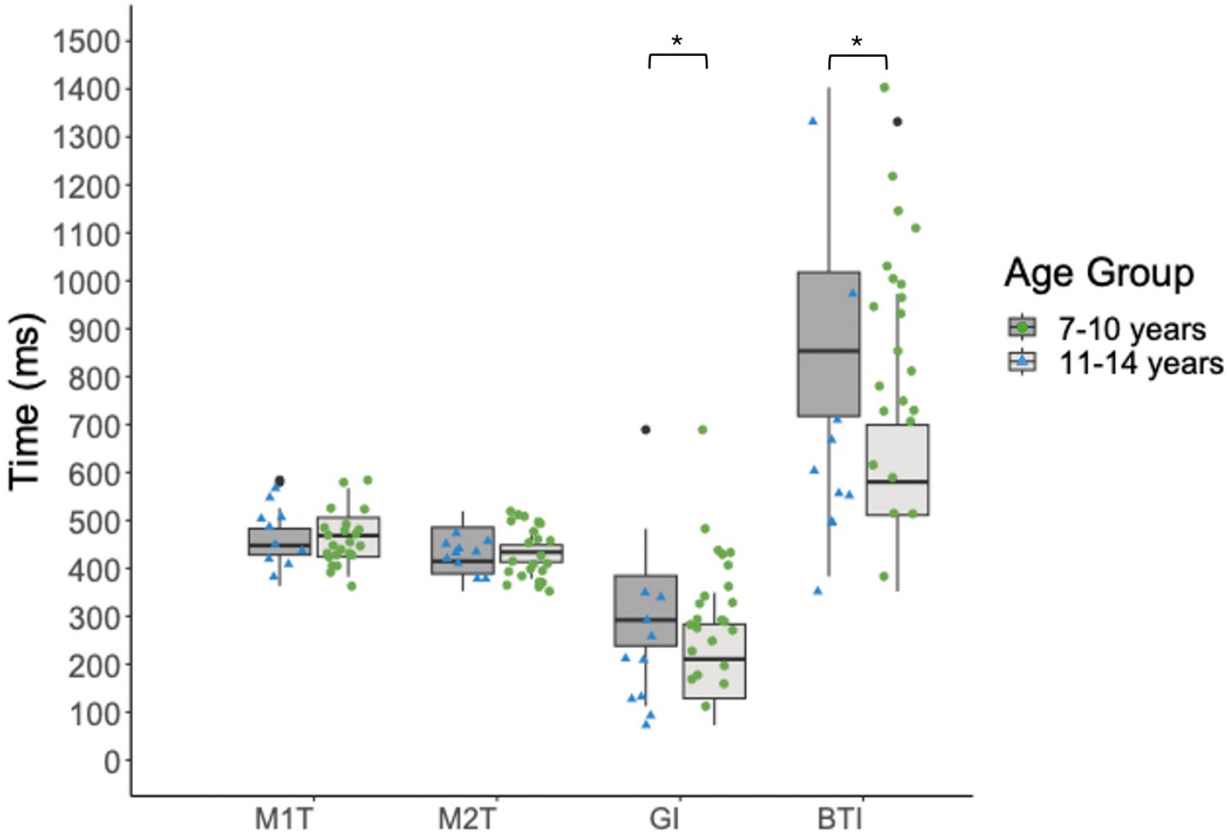


Figure 4. Boxplot with individual points to show distribution of performance in Reach to Bead Duration (M1T), Grasping Interval (GI), Reach to Needle Duration (M2T) and Threading Interval (BTI).

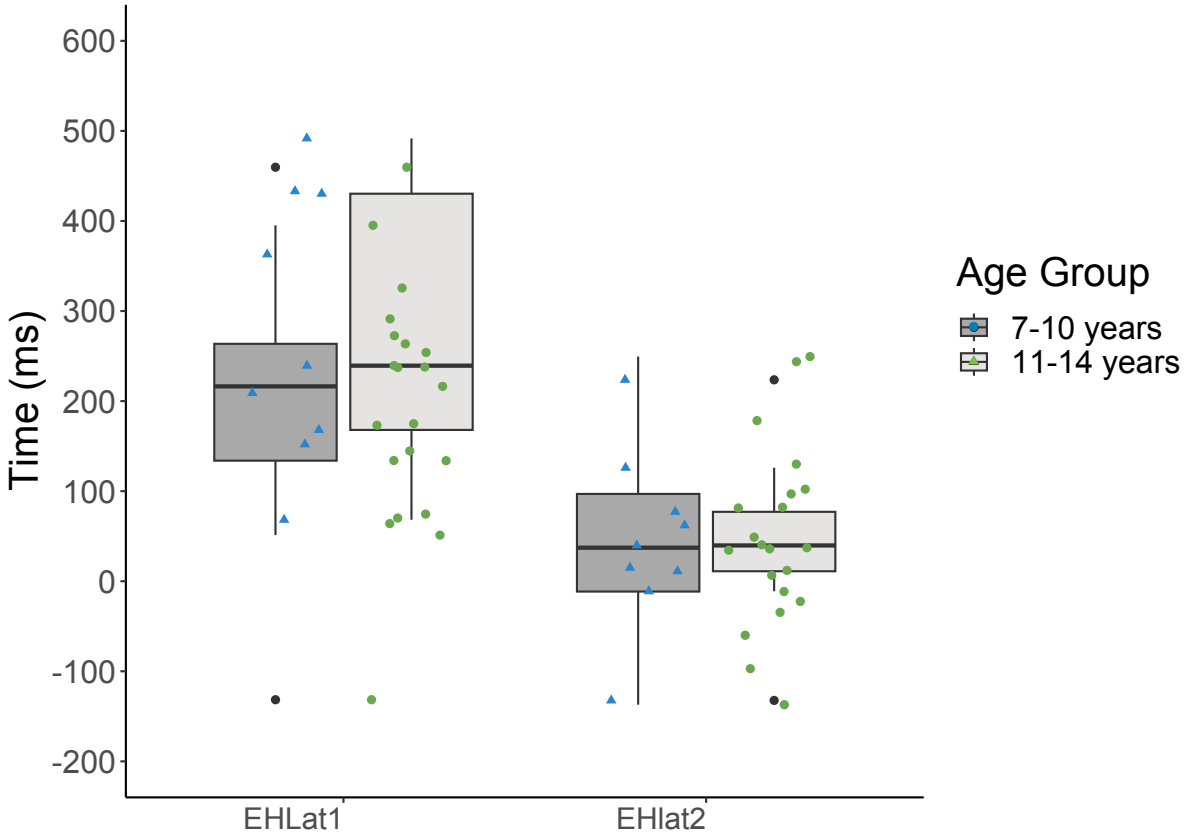


Figure 5. Boxplot with individual points showing the distribution of eye-hand latency for the first reaching movement (EHLat1) and the second reaching movement (EHlat2).

3.3 Case Studies

Using the scaled scoring method, a score of seven or lower identifies a child as at risk for motor problems and a score of 5 or lower identifies a case of probable DCD. Based on manual dexterity subtest scores, eight participants were identified as case studies, scoring at or below a scaled score of five (Figure 3). These cases were evaluated in detail to investigate their visual function and performance on the bead threading task. Results from the vision tests showed normal values in visual acuity and stereoacuity measures. Similarly, vergence facility (16.9 SD 4.8), accommodative facility (binocular: 12.5 SD 3.5; monocular: 10.7 SD 3.5), and amplitude of

accommodation (12.0 SD 2.0) were normal. DCD 13 and 19 had low negative fusional vergence (6 PD and 8 PD, respectively), indicating poor divergence ability. The Beery-VMI results for all the case studies were within expected values. Both the sight-word and phonemic reading tests showed normal results with most scores within two standard deviations from the expected mean except for one score slightly below the expected value in the phonemic decoding subtest.

Kinematic analysis of the bead threading task revealed varying performances in the case studies (Figure 6). When compared to previous values, six of the eight cases exhibited longer performance time for the bead threading task, with longest duration in the object manipulation phases (Niechwiej-Szwedo, Thai, et al., 2020). There were two children who scored very low on the manual dexterity MABC test but did not show any difficulties with the bead threading task.

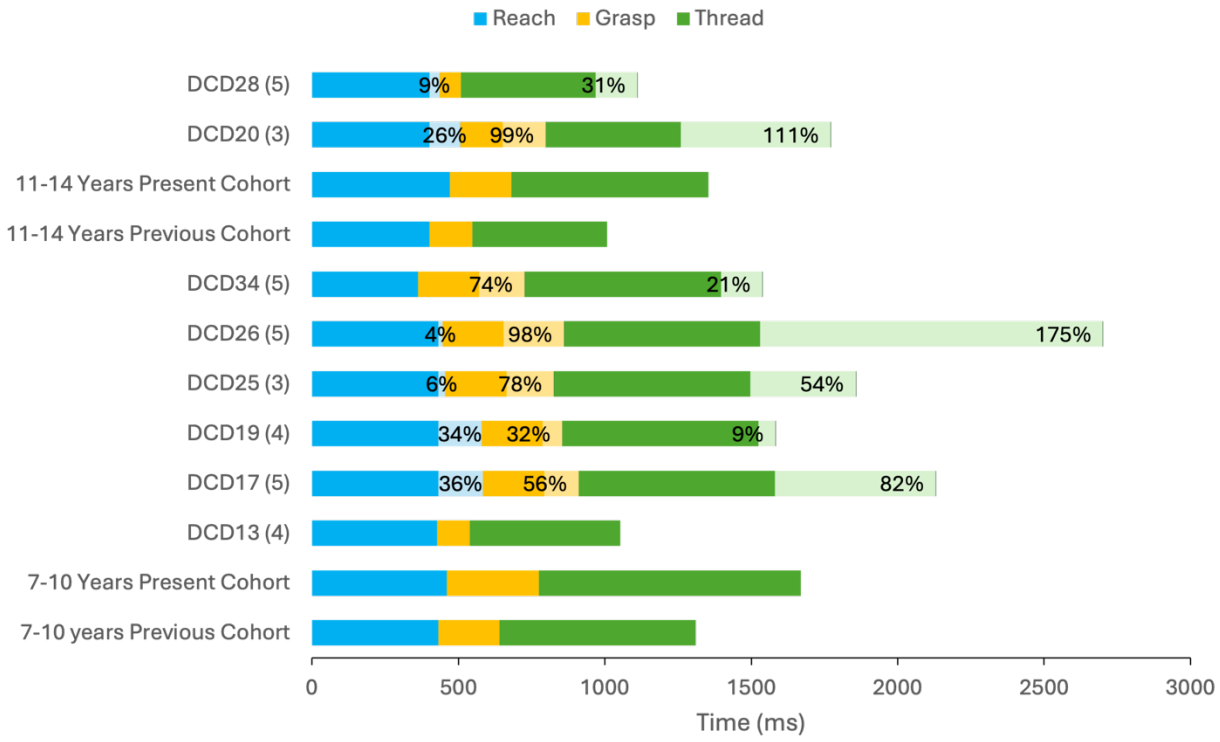


Figure 6. Graphical description of the kinematic results from the bead threading task for the eight case studies. The mean performance in the current cohort as well as a previously tested cohort (n=57, Niechwiej-Szwedo, Thai, et al., 2020) is also presented for reference. Each case and their scores for the manual dexterity test (in bracket) are listed along the ordinate. The abscissa represents the duration for each task component (reaching blue; grasping: orange; threading: green) where the solid color represents the mean duration found in the control group while the lighter section indicates the additional percentage of time needed to complete the task by the child in comparison to an age-matched cohort of children.

4.0 Discussion

This study aimed to examine the relationship between visual function and visuomotor ability in typically developing children with no medical diagnosis of a neurodevelopmental disorder. The testing included a comprehensive optometric assessment, standardized clinical tests of visuomotor integration, reading, fine and gross motor skills, as well as a kinematic test assessing eye-hand coordination. Results from the vision tests revealed that children fell within the age-expected range for some tests and outside of the expected age norms for accommodative facility, vergence facility, and accommodation amplitude. Importantly, the range of scores allowed a correlation analysis to be performed to determine if lower scores on visual tests are associated with poorer fine motor skills and altered hand-eye coordination profiles.

Most of the vision tests fell within age-expected norms except for vergence facility, binocular accommodative facility and amplitude of accommodation. Binocular accommodative facility was almost two standard deviations higher than the expected value (Scheiman et al., 1988; Scheiman & Wick, 2008). The study that established this normative value measured accommodative facility in 395 school-aged children (6-12 years) using the +/-2.00D flipper method (Scheiman et al., 1988). While the study establishing normative data used the same measurement technique as the one used in the current study, there could be variance in instructions or the possibility of the children gaining an advantage by looking ahead during the test before the lens is used. A more recent study exploring accommodative function in secondary school-aged children showed much more variance in the accommodation results and larger standard deviations (Mármol-Errasti et al., 2022). The latter study aligns more closely with the results of the current study as the accommodation performance we found falls within the 95% confidence interval of the study by Mármol-Errasti and colleagues.

Vergence facility and amplitude of accommodation both had lower than expected results in the current study. Vergence facility was 15% lower (i.e., 13.5 SD 3.9 compared to an expected value of 16.0 SD 2.6). Age-expected minimum values for amplitude of accommodation were determined using an equation adjusting for the gradual decrease in accommodation ability with age (15.0 – 0.25(age); (Hofstetter, 1950). Evaluation of each age group identified 21 children (66%) below the age expected minimum amplitude of accommodation. Our findings are similar to other studies which used the equation developed by Hofstetter and reported lower than expected performance across various age groups (Munsamy et al., 2023). The correlation analysis revealed some predictable significant relationships, for example, monocular and binocular accommodative facility were correlated (Wick & Hall, 1987). Similarly, a moderate correlation was found between binocular accommodative facility and vergence facility, consistent with evidence establishing a relationship between vergence and accommodative systems to further allow for maximum clarity in vision (Jiménez et al., 2004; Sweeney et al., 2014).

The cohort tested in this study performed as expected on the Beery-VMI and TOWRE-2 sight word efficiency and phonemic decoding tests. Motor performance, as evaluated by the MABC-2 test, was lower than expected, specifically on the manual dexterity subtest. Using the guidelines established in the MABC-2 manual, there were eight children in the cohort (23%) that scored at or below the 5% percentile in the manual dexterity test which indicates poor motor ability. Notably, none of the children had a formal medical diagnosis of motor difficulties. These results are consistent with other studies showing a downward trend in motor abilities; however, it is important to acknowledge that the results of one subtest do not provide sufficient evidence for a medical diagnosis of DCD (Gaul & Issartel, 2016).

Given the variation in visual function and motor performance scores, analysis was performed to evaluate the hypothesis that better visual function would be associated with higher scores for motor ability and more efficient visuomotor performance. Visual functions such as stereoacuity, accommodation and vergence, are all helpful with performing tasks which require binocular processing of depth cues, and consequently may impact performance of fine motor skills. For example, stereoacuity, vergence and accommodation work together to maintain single clear vision and provide information about the object location and extent in three-dimensional space. Thus, a positive correlation was expected. Counterintuitively, higher scores on the accommodation facility and vergence facility test were associated with lower total score and lower manual dexterity score on the MABC-2 test (i.e., negative correlation). A similar pattern of results was also seen in the bead threading task where higher amplitude of accommodation was associated with slower performance of the grasping and threading. This result is not consistent with previous studies that have examined the association between accommodation and motor capabilities (Niechwiej-Szwedo, Thai, et al., 2020a; Rafique & Northway, 2015). Accommodation is the ability of the ocular lens to adjust, allowing for stimulus at different distances to be brought into focus. Accommodative and vergence facility tests evaluate how fast the accommodative or vergence system can adjust to see clearly when looking at objects at different distances, while the amplitude of accommodation is the focusing ability that the patient can exert in response to a near target. The results showed a pattern opposite to our hypothesis: vergence facility and accommodative facility were negatively correlated with MABC-2 scores, suggesting that children who perform better on the motor tests have lower facility. Conversely, there was a positive correlation between amplitude of accommodation and total time taken to perform the bead threading task, indicating that children able to focus closer to the body take

longer to perform the grasping and threading movements. These results are surprising and contrast a previous study where higher amplitude of accommodation was found to be associated with better motor skill performance in a sample of 10 year-old children (Rafique & Northway, 2015). One plausible explanation is that our sample included children 7-14 years old, whereas in the other study the majority of children were younger than 10 years old. Amplitude of accommodation reduces with age, such that an eight-year-old child is expected to have value of 16D while 14 years old would have 14D of accommodative amplitude. Thus, it is possible that younger children tend to have higher accommodation, and also perform the task slower due to immature sensorimotor control, which contributes to the positive correlation. Another important consideration that might have affected the results is that the vision testing relies on children reporting their subjective experience, for example, they report when the target is blurry or clear. Although efforts were made to ensure that children understood the task, it is possible that some children had difficulty following the instructions. That is, facility in the younger children might be overestimated if the children responded 'clear' while the letter was not fully clear.

4.1 Overall Reduction of Manual dexterity Performance

An important finding from this study is a trend towards an overall decrease in motor performance in this cohort when compared to previous studies or normative data. Specifically, in the current cohort the overall MABC-2 scores were slightly lower but within expected ranges, however, the manual dexterity subtest scores fell one standard deviation below the expected range. These results are consistent with a recent study that explored motor development in typically developing children to assess the hypothesis that increase in technology use might be associated with a reduction in manual dexterity skills. The results from that study demonstrated a significantly worse performance of motor skills compared to age expected norms. While the

older children performed better than the younger children, providing evidence for developmental progress, their scores were lower compared to the expected performance levels (Gaul & Issartel, 2016; Niechwiej-Szwedo, Meier, et al., 2020). The current study adds to this body of literature highlighting a significant decrease in manual dexterity skills which may be arising due to fewer opportunities to practice manual skills with the increased use of digital technology and changing learning environments.

Similarly, when evaluated with the bead threading task using the kinematic measures, such as grasping and threading intervals, there was also a decrease in performance when compared to previously published studies (Niechwiej-Szwedo, Meier, et al., 2020; Niechwiej-Szwedo, Thai, et al., 2020). Grasping, threading and total movement time were all outside of the confidence interval of the cohorts tested in the previous studies, indicating a decrease in performance. Notably and consistent with the previous study, there was a significant difference in the object manipulation measures (i.e., grasping and threading) for the beads task when comparing performance between older and younger age groups. This result is consistent with the Gaul (2016) paper showing that children are still progressing though motor development, but they are progressing slower and falling short when compared to cohorts tested in previous studies.

There may be several explanations for the overall reduction in manual dexterity performance on the clinical tests and the bead threading task. The first potential cause is the recent COVID-19 pandemic spanning from 2020 to 2022 (Rebelo et al., 2024) . Children were moved to remote education options relying heavily on technological solutions, which may have impacted their exposure to opportunities to practice manual dexterity skills. Recent studies have begun to address the social and developmental effects of the global pandemic on children's

development (Araújo et al., 2021; Pajek, 2022; Rebelo et al., 2024). This change in the typical environment could have profound effects on many aspects of development, including motor performance and ability.

In addition to the COVID-19 pandemic reducing the opportunities for in-person activities and forcing a move to a digital world, recent advances in technology lead to a general increase in the access to technology such as touch tablets. These changes in education settings could impact the overall trajectory of motor development and experiential learning that children are exposed to. The study conducted by Gaul et al., outlines the importance of fine motor skill development, and lack thereof, which was present even before the pandemic. With the increasing downward trend of motor skill development and longer trajectories for motor skill acquisition, it will be important to continue to investigate the impact of technology on motor skills learning and develop assessment tools to monitor the trends. While children are taking more time to achieve typical performance of their age group, it will be important to evaluate tasks more specific to each child with more emphasis on motor learning strategies. Or exploring if the time to achieve certain markers is consistently delayed, determining if current learning environments result in a true delay of development and adjusting timelines accordingly. A future investigation would be needed to establish whether motor performance improves in young adults.

4.2 Case Study Discussion

The case studies were selected based on low manual dexterity subtest scores on the MABC-2 test. Further analysis into the other tests and measures was then conducted. Notably, these children were recruited as typically developing children as they did not have a formal diagnosis of a neurodevelopmental disorder. Difficulties in motor control were mostly confirmed

in the bead threading task. When segments of the bead threading task were further evaluated, task time was typically increased due to longer bead grasping and threading intervals. Thus, suggesting that children have difficulties with object manipulation. While the consistency of results across the clinical and experimental task is encouraging, vision testing did not reveal any additional insight regarding why these motor difficulties are present.

4.3 Limitations

This study is part of a larger project, and to date recruited a sample size of 35 children. More participants will be recruited but that is outside the timeframe of this thesis. Although 35 children participated, there are several instances where a full battery of tests could not be administered due to equipment or operator error, incomplete surveys, lack of time, or simply the inability of the child to complete the tasks (Table 3). The loss of data impacted the analysis, for example, sample size was reduced to 25 for some of the correlations, which affects the ability to detect significant associations. In addition, the number of correlation analyses performed presents a risk of Type I error, which is when the null hypothesis is falsely rejected. Applying a Bonferroni correction renders all correlations non-significant, which may hide some real and important relationships.

The negative correlations with the MABC-2 scores suggest that better motor performance is associated with lower vergence and accommodative facility. Vergence and accommodative functions both play important roles in performing tasks at near in the peripersonal space (Fincham & Walton, 1957) so the negative correlation does not align with expected, previously observed results. The majority of the vision testing was conducted by an optometry student trained to administer the tests by a registered optometrist. Therefore, the results of the optometric

test are most likely valid. The clinical test of motor skills and the bead threading task were also performed according to standardized guidelines. Thus, the unexpected correlations are difficult to explain. A study with a larger sample size is necessary to reveal the true nature of these relationships.

4.4 Future Directions

There are promising directions that can be explored in future studies. First, it will be important to increase the sample of typically developing children, and to recruit children with diagnosed DCD to further explore the association between vision and motor skill development. This study used clinically standardized tests to help characterize the participants, such as the MABC-2 and Beery-VMI. These tools are very important, but they present with their own problems. For example, these tests take a long time to administer and they do not provide insight into the cause of the underlying problem. As more experimental methods are used to evaluate hand-eye coordination and more studies explore the link between performance and other measures, more objective and less time-consuming measures can be introduced into clinical practice.

Another challenge that can be combatted with the further exploration of experimental measures is targeting the specificity of tests and establishing a more consistent diagnosis of DCD. For example, there is a prevalence of DCD reported worldwide, but there is also a large variance in the criteria used for diagnosis. Developing more specific assessment tools and consistent measures could help with developing targeted treatment plans.

This study provided a unique opportunity for children to participate in simple, yet enjoyable tasks with and without using technology. The majority of the children were very receptive to the

experience and learning about research. Going further and building from this experience, the ability to use new technology and slowly move this type of testing outside of the lab environment to various practitioner offices or even educational settings should be considered. Not only would this increase the scope of assessments, but it also makes this work more accessible and available to the public. The eventual goal of using experimental tasks, like the bead threading task, to help identify children with movement disorders and/or neurodevelopmental disorders, making diagnostic testing fun and accessible would be a step in that direction. As the study continues to recruit a larger control group and the experimental group, the increasing numbers will help further establish relationships between the variables measured and how they interact.

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