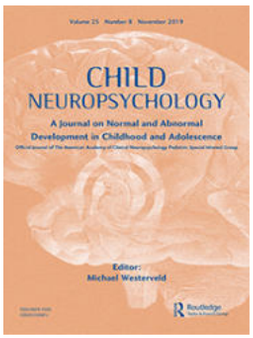

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Development of rule-based eye-hand-decoupling in children and adolescents

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ABSTRACT

In the present study, we characterize how the ability to decouple guiding visual information from a motor action emerges during childhood and adolescence. Sixty-two participants (age range 8–15 yrs.) completed two eye-hand coordination tasks. In a direct interaction task, vision and motor action were in alignment, and participants slid their finger along a vertical touch screen to move a cursor from a central target to one of four peripheral targets. In an eye-hand-decoupled task, eye and hand movements were made in different planes and cursor feedback was 180° reversed. We analyzed whether movement planning, timing and trajectory variables differed across age in both task conditions. There were no significant relationships between age and any movement planning, timing, or execution variables in the direct interaction task. In contrast, in the eye-hand-decoupled task, we found a relationship between age and several movement planning and timing variables. In adolescents (13–15 yrs.), movement planning and timing was significantly shorter than that of young children (8–10 yrs.). Eye-hand-decoupled maturation emerged mainly during late childhood (11–12 yrs.). Notably, we detected performance differences between young children and adolescents exclusively during the eye-hand decoupling task which required the integration of rule-based cognitive information into the motor action. Differences were not observed during the direct interaction task. Our results quantify an important milestone for eye-hand-decoupling development in late childhood, leading to improved rule-based motor performance in early adolescence. This eye-hand-decoupling development may be due to frontal lobe development linked to rule-based behavior and the strengthening of fronto-parietal networks.

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KEYWORDS
Cognitive-motor integration; direct mapping; visuomotor performance; youth; vision and motor action

Childhood and adolescence represent a crucial period for the development of several cognitive and motor functions, providing important experience for future interaction with the surrounding world and environment (Piek, Baynam, & Barrett, 2006). The timing and course of this development are, therefore, important to understand (Adolph & Franchak, 2017). For this reason, cognitive and motor development in youth have

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already been fairly well characterized over the past century; however, the majority of research has studied cognitive and motor functions and their developmental patterns separately (Lubans, Morgan, Cliff, Barnett, & Okely, 2010; Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002; van der Fels et al., 2015). Studies reported that cognitive abilities (such as response inhibition and social functions) and fundamental motor functions (such as reaching) develop at different rates during childhood and adolescence with cognitive abilities emerging later than goal-directed reaching abilities (Lubans et al., 2010; Paus, 2005). For example, the development of higher-order cognitive processing, such as executive function and response inhibition peaks between the ages of 10 to 13 years, whereas social cognitive function development demonstrates a rather linear development into late adolescence (Paus, 2005). In contrast, the development of basic standard mapping motor function, such as direct reaching and grasping for objects, peaks earlier, around the age of 10 (Lubans et al., 2010).

Several research studies have shown that the development of cognition and motor function are more connected than previously thought, on both anatomical and functional levels (Adolph & Franchak, 2017; Diamond, 2000; Pangelinan et al., 2011). Further, the relationship between cognition and motor functions is even stronger when higher-order cognitive functions are involved (van der Fels et al., 2015). To address the fact that most research has investigated cognitive and motor skills separately, a growing area of research involves examining visuomotor functions when elements of thinking and moving are performed at the same time (Gorbet & Sergio, 2016). Using rule-based eye-hand-decoupling (also known as "cognitive-motor integration"), this research has further demonstrated important connections between cognitive and motor functions (Gorbet & Sergio, 2009, 2019; Gorbet, Staines, & Sergio, 2004). It is important to note the ways in which rule-based eye-hand-decoupled tasks differ from direct interaction motor tasks. In direct motor interaction tasks, the spatial locations of the guiding sensory information and the required motor action are in alignment. Looking at and then picking up an apple is an example of a direct interaction task. In contrast, examples of rule-based eye-hand-decoupled tasks include parking a car in reverse or when a hockey player skates to the left while stickhandling the puck and watching out for other players on the right. These tasks require decoupling of vision and action because the eyes must move in a different direction and/or in another plane than the performed motor action. Importantly, eye-hand-decoupled tasks also require the integration of context-specific rules (Gorbet & Sergio, 2009).

Eye-hand-decoupling is crucial for many every day and sport-related activities (Brown, Dalecki, Hughes, Macpherson, & Sergio, 2015). Thus, the development of eye-hand-decoupling in childhood or adolescence provides an important foundation for complex rule-based eye-hand coordination later on in life that goes beyond fundamental motor functions such as direct grasping, reaching, walking and running (Lubans et al., 2010). Previous rule-based eye-hand decoupled studies in adult human and non-human primate brains have shown that this function heavily relies upon the frontoparietal networks (Hawkins, Sayegh, Yan, Crawford, & Sergio, 2013; Sayegh et al., 2014). These networks have also been associated with eye-hand-decoupled performance deficits in populations with neurologic disorders such as Alzheimer's risk and mild cognitive impairment (Hawkins, Goyal, & Sergio, 2015; Salek, Anderson, & Sergio, 2011).

In childhood and adolescence, the strengthening and development of white matter tracts in general have been reported to occur between the ages of 4 to 22 years, and 5 to 18 years, respectively (Giedd, 1999; Schmithorst, Wilke, Dardzinski, & Holland, 2002), mainly due to a further thickening of axons and increasing myelination (Paus, 2010; Paus et al., 1999). In addition, grey matter development of the prefrontal and parietal cortex, areas that are linked to rule-based cognitive functions, peaks at around 10 to 13 years of age (Paus, 2005). However, the development of the ability to control rule-based eye-hand decoupling has not been studied yet. In the present study, we, therefore, aim to provide novel insight into the time course of rule-based eye-hand decoupling development. Given the later development of cognitive versus goal-directed reaching abilities in children and our current knowledge of the networks and brain areas involved in rule-based eye-hand-decoupling, we expect that the rate of development will be constrained by cognitive development rather than motor development. We, therefore, hypothesize increased eye-hand decoupled performance in adolescents compared to children. In contrast, since the development of skills needed for direct interaction tasks peaks in childhood (Lubans et al., 2010), we do not expect that children and adolescents will perform differently during direct interaction, where the guiding visual information and motor response are spatially aligned.

Material and methods

Participants

Sixty-two right-handed participants were involved in the study (28 girls, 34 boys, 8–15 yrs., mean 11.97 ± 1.87 yrs.). We obtained demographic information from all participants with questionnaires, and handedness was assessed by the Edinburgh handedness inventory (Oldfield, 1971). At the time of testing, all participants had normal or corrected to normal vision, were reported to be healthy, and did not receive a gift for their study participation. The study protocol was approved by the Human Participants Review Sub-Committee, York University's Ethics Review Board, and conformed to the standards of the Canadian Tri-Council Research Ethics guidelines. Parents and children/adolescents provided written informed consent/assent before participating in this study.

Procedures

All participants performed two visuomotor transformation tasks, similar to those previously used in eye-hand-decoupled studies of adult and elderly populations (Brown et al., 2015; Hawkins & Sergio, 2014). Participants sat on a chair at a desk where the experimental task was presented on an Acer Iconia 6120 dual-touchscreen laptop, with a touch screen (14′ LCD display, 1366 × 768 pixel resolution) in the vertical plane and one in the horizontal plane (i.e., where a keyboard would usually be found). The first experimental condition was a direct interaction, standard visuomotor mapping task (condition "Direct"), where the spatial location of the viewed target and the required movement were in alignment. This task involved sliding a finger along the vertical touch screen to move a cursor from the screen center to a cued peripheral

target. The second experimental condition was a non-standard mapping task which required eye-hand-decoupling (condition "Decoupled"). This task required two levels of decoupling between vision and action: Targets were again viewed on the vertical touch screen, but participants had to slide their finger (1) along the horizontal touch screen, and (2) in the opposite direction of the cued peripheral target to displace the cursor (feedback reversal). That is, to move the cursor to the left, they had to slide their finger to the right, etc. (cf., Figure 1(a)).

Targets for movement presented on the vertical touch screen were of 20 mm diameter, red-colored and presented to the left, right, above or below the central target (also 20 mm in diameter). The distance between the centers of the peripheral and central target (i.e., the screen center) was 75 mm. The task itself was displayed on a 170 × 170 mm black square with the surrounding background colored grey, in order to maintain a constant visual border. There were a total of 20 trials (i.e., 5 to each peripheral target) per experimental condition (ie. Direct or Decoupled), thus, altogether 40 test trials per participant. Trials within each of the two visuomotor conditions were presented in blocks (one block per condition for each participant). The order of performing both experimental conditions was randomized across participants in each group. In addition, to ensure task comprehension, each participant performed two practice trials in each direction in both experimental conditions.

The trial timing and responses of participants were as follows for the Direct condition: (1) a green colored center target was presented on the vertical touch screen, (2) participants touched the target with the index finger of their dominant hand. The target then changed its color to yellow. (3) After holding the center target for 4000 ms a red peripheral target appeared and the center target disappeared, serving as the "go-signal" for participants to concurrently look at and slide their index finger along the touch screen to move the cursor to the target. (4) Once the peripheral target was reached and held for 500 ms, the peripheral target disappeared and the trial ended. (5) The next trial began with the presentation of the center target after an inter-trial interval of 2000 ms. The sequence was the same for the Decoupled condition except that while eye movements were made to the cued target location (i.e., eye movement requirements did not differ between the conditions), the finger moved on the horizontal touchscreen in the opposite direction of the target.

Participants were instructed to look at the cursor and move it to the target as quickly and accurately as possible, and ambient distractions were kept to a minimum. Participants had full vision of their hand and fingers. The experimenter monitored participant's eye movements during the experiment and if incorrect eye movements were made, participants were reminded to always look towards the target and not to their hand. Those incorrect movements were less than 2% of the trials and were eliminated before final data analysis.

Data processing

Response timing, finger position (x, y coordinates; 50 Hz sampling rate), and error data were recorded during each trial. Saved raw data were then converted into MATLAB readable format using a custom written C++ application. The data were analyzed using custom-written software (Matlab, The Mathworks, Natick, MA, USA). Individual

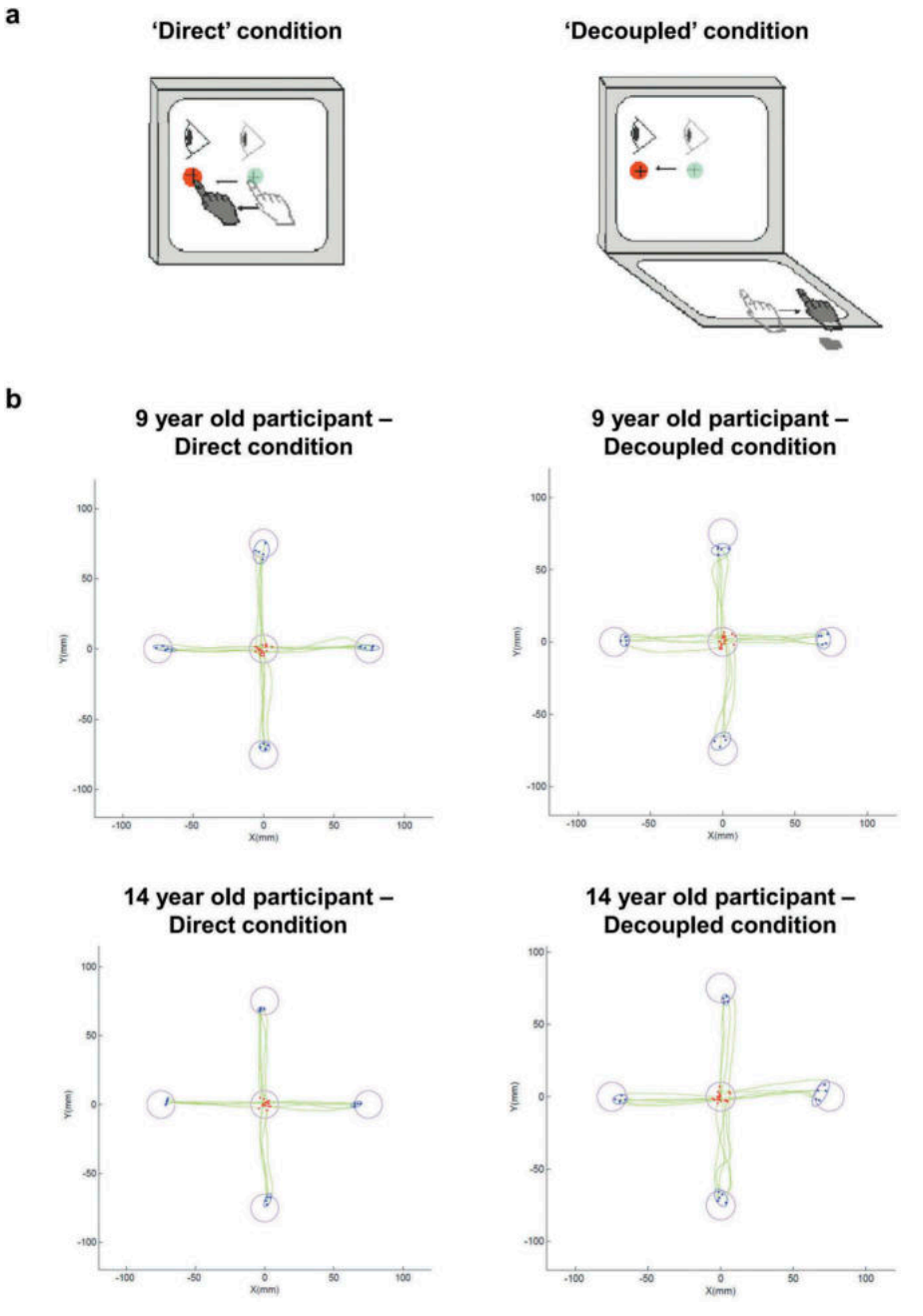

Figure 1. (a) Schematic drawing of the experimental conditions (Direct, Decoupled). Visual stimuli were presented on the vertical monitor for both conditions. The central green circle (home target), was the starting position for gaze (light grey eye) and the hand (light grey hand) for each trial. Dark grey eye and hand symbols denote the instructed eye and hand movements for each task. Red circles denote the peripheral target, presented randomly in one of four locations (left, up, right, or down relative to the home target). The dark crosshair denotes the cursor feedback provided during each condition. (b) Typical full hand path data of one child and one adolescent, performing the Direct and Decoupled condition. Note the poorer hand path in the Decoupled condition compared to the Direct condition for both participants, but the similar movement trajectories, accuracy, and precision of the 9 year old child and the 14 year old adolescent in both conditions.

movement trajectories derived from the cursor location were first low-pass Butterworth filtered at 10 Hz. Trials were deemed errors if the finger/cursor left the center target prior to the required center hold time at the start of each trial (<4000 ms), reaction time was too short (<150 ms), reaction time was too long (>8000 ms) or movement time was too long (>10,000 ms). Trials in which the first ballistic movement exited the boundaries of the center target in the wrong direction (i.e., greater than 90° from a straight line to the correct target location) were coded as direction reversal errors (DR). Direction reversal error trials were excluded from calculations of the mean values of dependent measures (see below); however, the number of direction reversal errors made by participants were counted and included as a dependent variable. Movement onset was defined as the time after the disappearance of the central target at which the velocity of the hand movement first reached 10% of the peak velocity obtained for the trial. Initial movement offsets were defined as the first point at which movements stopped or slowed significantly, i.e., the end of the first initial movement before any corrective movements. The total movement endpoint (i.e., after any small correctional movements made after the first ballistic movement) was then scored as the point at which velocity reached a final zero-crossing and position data plateaued (i.e., when subjects stopped the cursor inside the peripheral target). Data scoring was verified visually to ensure that computed offsets by the program were accurate. Further movement timing and execution outcome measures were then calculated as described in detail below.

Dependent measures

In accordance with previous work on rule-based eye-hand-decoupling using similar test setups in young adults and elderly study populations (Gorbet & Sergio, 2009; Hawkins & Sergio, 2014; Salek et al., 2011), we analyzed various movement planning, timing, and execution variables during both, the Direct and Decoupled visuomotor task conditions. The variables are described in detail in the following section.

Performance planning and timing

Outcome metrics categorized as movement planning variables included reaction time (RT). Metrics categorized as movement timing variables included initial movement time (IMT), total movement time (TMT), corrective movement time (CorrMT), and peak velocity (PeakVel). In detail, mean reaction time across trials was calculated as the time between the appearance of the peripheral target and movement onset, i.e., the time at which the participant began movement execution by sliding the cursor towards the target, in milliseconds. Initial movement time was calculated as the time difference between movement onset and the first distinct movement correction of the initial muscle impulse after response onset (cf., above "Data processing" section), in milliseconds. Total movement time was calculated between movement onset and final movement offset (i.e., reaching the peripheral target, cf., above "Data processing" section). Corrective movement time was calculated as the difference between total movement time and initial movement time, i.e., the time the participants required for movement corrections, in milliseconds. Note that for any trial where the participant's first ballistic movement ended in the target, initial movement time and total movement time would be equal and corrective

movement time would equal zero. The peak velocity was the maximum velocity during the total movement, in cm/s. Direction reversal errors were recorded as a percentage of completed trials.

Performance execution

Outcome metrics categorized as movement execution variables included initial path length, full path length, corrective path length, absolute error, and variable error. In detail, measurements of the length of finger trajectories (i.e., distance traveled) on the touch screens were recorded for each trial. The initial path length was quantified as the distance in mm between the start and end of the initial cursor movement (i.e., the distance covered during the initial movement time), in millimeters. Full path length was calculated as the distance between the start and end location of the cursor movement including any movement corrections made after the ballistic movement, in millimeters. Movements that resulted in curves or deviations from a straight path between the central and peripheral target would thus result in a longer path length. Corrective path length was quantified by subtracting initial path length from full path length, in millimeters. The absolute error, i.e., the endpoint accuracy, was determined as the distance between the average movement endpoint for each target location (Σ x/n, Σ y/n) and the actual target position (defined by the x and y coordinates at the center of the target), in millimeters. Variable error, i.e., the endpoint precision, was determined as the distance between the endpoints of the individual movements ($\sigma 2$) from their mean movements, in millimeters.

Statistical analysis

To test our hypothesis, we investigated the general relationship between visuomotor task performance and age by correlating the outcomes of all dependent variables (RT, IMT, TMT, CorrMT, PeakVel, IPL, FullPL, CorrPL, AE, VE) separately for each condition (Direct, Decoupled) with the age of the participants, using a Pearson linear regression analysis. In addition, on an explanatory basis and based on the results shown in Figure 2 and existing literature of eye-hand coordination development in youth (e.g. (Albines, Granek, Gorbet, & Sergio, 2016), we examined the time course of Direct interaction and Eye-hand-decoupled development across Young children (8–10 years), Children (11–12 years), and Adolescents (13–15 years). For all dependent measures (cf., above), effects of group (Young children, Children, Adolescents) and condition (Direct, Eye-hand-decoupled) were analyzed using a repeated-measures mixed ANOVA, with group (Young children, Children, Adolescents) as a between-subjects factor and condition (Direct, Decoupled) as a within-subjects factor. When there were significant main or interaction effects, Bonferroni post hoc tests corrected for multiple comparisons were used. Note that direction reversal errors were only applicable in the Eye-hand-decoupled condition, such that we used a one-way ANOVA. Also, a separate analysis using sex as the main effect was run to test for any sex-related behavioral differences. Trials with values that were >2 standard deviations (SDs) away from the mean for a given condition in a given group were considered outliers and removed before statistical analysis. All remaining

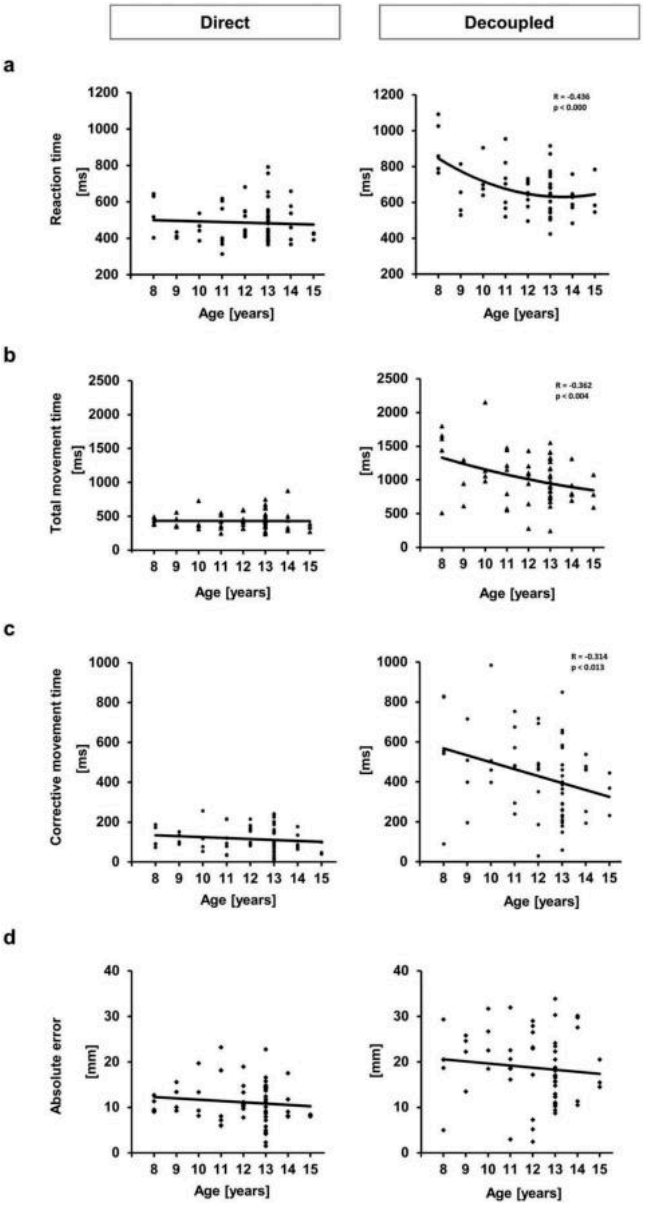

Figure 2. Relationship between age and (a) reaction time, (b) total movement time, (c) corrective movement time, and (d) absolute error values for study participants in the Direct condition and the Decoupled condition. Note the flat and non-significant trend lines for all four variables in the Direct condition as well as for the movement execution variable (d) in the Decoupled condition. In contrast, note a significant relationship between age and visuomotor performance in the Decoupled condition for the movement planning (a) and timing (b, c) variables.

data were checked for normal distribution (Shapiro-Wilk's test) and sphericity (Mauchly's test) and were Greenhouse-Geisser corrected where necessary. All statistical analyses were performed using SPSS statistical software (IBM Inc.). Statistical significance levels were set to $\alpha = 0.05$.

Results

Most notably, we found a significant relationship between age and visuomotor performance for movement planning and movement timing variables in the Decoupled condition but not in the Direct condition. The effect of age on visuomotor performance in both task conditions is described in more detail in the section "*Relationship between visuomotor task performance and age*", and statistical outcomes of the correlation analysis are summarized in Table 1. In addition, we found that eye-hand-decoupled movement planning and timing were significantly faster in adolescents compared with young children. Visuomotor performance differences across young children, children, and adolescents in both task conditions are described in the section "*Visuomotor task performance in Young children, Children, and Adolescents*". Descriptive statistics are summarized in Table 2, and statistical outcomes of the repeated-measures mixed ANOVA for all dependent variables by group (Young children, Children, Adolescents) and condition (Direct, Decoupled) are summarized in Table 3.

The analysis using sex as a main effect yielded no significant differences for any dependent variables, except for peak velocity in the Direct condition ($F(1,61) = 4.46$, $p < 0.039$), showing a higher peak velocity in boys (198 ± 51 cm/s) than in girls (175 ± 28 cm/s). Since this visuomotor condition did not show any significant effects linked to age and visuomotor performance, we merged data across sexes. Figure 1(b) shows raw data examples of typical movement trajectories of one 9-year-old participant and one 14-year-old participant performing the Direct and the Decoupled conditions. Note that the movement trajectories look very similar between both participants in both task conditions.

Table 1. Statistics of the correlation analysis between age and all dependent variables (RT, MT, TMT, CorrMT, BallPL, FullPL, CorrPL, AE, VE, DR) in conditions Direct and Decoupled. Note that DR was only applicable in the Decoupled condition. Abbreviations: RT = Reaction time, IMT = Initial movement time, TMT = Total movement time, CorrMT = Corrective movement time, PeakVel = Peak Velocity; IPL = Initial pathlength, FullPL = Full pathlength, CorrPL = Corrective pathlength; AE = Endpoint accuracy, VE = Endpoint precision; DR = Direction reversal errors.

Variables	Condition	r (60)	p – value
Age * RT	Direct	−0.061	0.636
	Decoupled	−0.436	0.000
Age * IMT	Direct	0.075	0.561
	Decoupled	−0.294	0.020
Age * TMT	Direct	−0.009	0.948
	Decoupled	−0.362	0.004
Age *CorrMT	Direct	−0.137	0.290
	Decoupled	−0.314	0.013
Age * PeakVel	Direct	0.049	0.705
	Decoupled	0.152	0.238
Age * IPL	Direct	0.064	0.620
	Decoupled	0.126	0.330
Age * FullPL	Direct	−0.136	0.290
	Decoupled	−0.220	0.085
Age * CorrPL	Direct	−0.143	0.269
	Decoupled	0.269	0.077
Age * AE	Direct	−0.117	0.365
	Decoupled	0.111	0.392
Age * VE	Direct	−0.052	0.690
	Decoupled	0.017	0.897
Age * DR	Decoupled	−0.150	0.244

Table 2. Descriptive statistics of the repeated-mixed ANOVA and the one-way ANOVA for DR. Abbreviations: RT = Reaction time, IMT = Initial movement time, TMT = Total movement time, CorrMT = Corrective movement time, PeakVel = Peak Velocity; IPL = Initial pathlength, FullPL = Full pathlength, CorrPL = Corrective pathlength; AE = Endpoint accuracy, VE = Endpoint precision; DR = Direction reversal errors.

Variable	Condition	Young Children	Children	Adolescents
			[ms]	
RT	Direct	488 ± 98	481 ± 105	487 ± 111
	Decoupled	771 ± 170	669 ± 115	635 ± 113
IMT	Direct	312 ± 71	285 ± 63	331 ± 127
	Decoupled	727 ± 260	541 ± 188	568 ± 222
TMT	Direct	435 ± 112	417 ± 104	436 ± 145
	Decoupled	1266 ± 467	1002 ± 349	940 ± 290
CorrMT	Direct	123 ± 57	132 ± 61	105 ± 69
	Decoupled	540 ± 252	462 ± 203	372 ± 172
			[mm/s]	
PeakVel	Direct	184 ± 50	189 ± 38	187 ± 45
	Decoupled	90 ± 31	121 ± 48	110 ± 38
			[mm]	
IPL	Direct	63 ± 3	63 ± 5	63 ± 5
	Decoupled	55 ± 8	58 ± 8	59 ± 8
FullPL	Direct	71 ± 4	71 ± 3	70 ± 2
	Decoupled	76 ± 5	76 ± 5	75 ± 4
CorrPL	Direct	8 ± 4	8 ± 4	7 ± 5
	Decoupled	21 ± 10	19 ± 9	16 ± 8
AE	Direct	12 ± 3	12 ± 5	11 ± 5
	Decoupled	22 ± 7	18 ± 9	18 ± 7
VE	Direct	8 ± 3	8 ± 3	8 ± 3
	Decoupled	9 ± 4	7 ± 4	8 ± 3
			[count %]	
DR	Decoupled	3 ± 3	4 ± 3	3 ± 2

Table 3. Statistical outcome repeated-measures mixed ANOVA of group (Young Children, Children, Adolescents) and condition (Direct, Decoupled) for all dependent variables (RT, IMT, TMT, CorrMT, BallPL, FullPL, CorrPL, AE, VE) and the one way ANOVA for DR. Abbreviations: RT = Reaction time, IMT = Initial movement time, TMT = Total movement time, CorrMT = Corrective movement time, PeakVel = Peak velocity; IPL = Initial pathlength; FullPL = Full pathlength, CorrPL = Corrective pathlength; AE = Endpoint accuracy, VE = Endpoint precision; DR = Direction reversal error; YC = Young children, AD = Adolescents.

	Group (Young children, Children, Adolescents)			Condition (Direct, Decoupled)			Group x Condition			Significant post hoc outcomes
Variable	F (2,59)	p - value	η^2	F (1,59)	p - value	η^2	F (2,59)	p - value	η^2	p - value
RT	1.98	0.147	0.063	198.29	0.000	0.771	7.55	0.001	0.204	0.005 (YC x AD)
IMT	1.90	0.159	0.060	147.57	0.000	0.714	4.68	0.013	0.137	
TMT	2.71	0.075	0.084	247.72	0.000	0.808	5.72	0.005	0.162	0.017 (YC x AD)
CorrMT	3.41	0.040	0.103	183.69	0.000	0.757	3.26	0.045	0.099	0.037 (YC x AD)
PeakVel	0.82	0.446	0.027	271.52	0.000	0.821	1.84	0.168	0.059	
IPL	1.10	0.340	0.036	36.12	0.000	0.380	1.27	0.289	0.041	
FullPL	0.71	0.496	0.023	45.50	0.000	0.435	0.21	0.814	0.007	
CorrPL	1.84	0.168	0.059	91.10	0.000	0.607	1.10	0.341	0.036	
AE	1.01	0.372	0.033	62.92	0.000	0.516	0.99	0.379	0.032	
VE	0.123	0.884	0.004	0.001	0.981	0.000	0.41	0.664	0.014	

One-way ANOVA direction reversal error in Decoupled condition:
DR F (2,61) = 1.99, p = 0.309

Relationship between visuomotor task performance and age

Notably, in the Decoupled condition, we observed a significant relationship between age and reaction time ($r_{(60)} = -0.436$, $p < 0.000$), initial movement time ($r_{(60)} = -0.294$, $p < 0.02$), total movement time ($r_{(60)} = -0.362$, $p < 0.004$), and corrective movement time ($r_{(60)} = -0.314$, $p < 0.013$). The remaining dependent variables of the Decoupled condition and all variables of the Direct condition did not show a significant relationship with age (all $p \geq 0.238$). The main results are visualized in Figure 2, which contains scatter plots with the fitted regression lines showing the relationship between the performance variable and age for (**a)** reaction time, (**b)** total movement time, (**c)** corrective movement time, and (**d)** absolute error. Results associated with the Direct task condition are shown in the left column and results for the Decoupled condition are shown in the right column. Notably, significant relationships between age and performance variables were only found in the Decoupled task condition (Figure 2 (a-c), right column) but not in the Direct task condition (Figure 2(a–d), left column).

Note that the significant relationships showed the highest r-scores (i.e., the best fit for the present data) when using a second-order function for reaction time (see Figure 2(a)), but in contrast, a linear regression for total movement time (see Figure 2(b)) and corrective movement time (see Figure 2(c)). The regression curve of the second order function trendline of the reaction time in the Decoupled task decreases continuously from the age of 8 years until it plateaus between the ages of 12 and 13 (cf., Figure 2(a), right column). This was in contrast to the linear trend lines of the total movement time and corrective movement time in the Decoupled task condition, which continue to decrease throughout the range of ages tested (cf., Figure 2(b,c), right row). In contrast, the non-significant trend lines in the graphs for the Direct task condition (Figure 2(a–d), left row) are rather horizontal, i.e., they do not show performance changes with age, for all variables tested. This lack of a significant relationship between age and performance was also observed for all movement execution variables in the Decoupled condition (e.g., Absolute error in Figure 2(d), right column).

Visuomotor task performance in young children, children, and adolescents

ANOVA yielded a significant main effect of group (Young children, Children, Adolescents) for corrective movement time ($F_{(2,59)} = 3.405$, $p = 0.040$, $\eta^2 = .103$) but no effects for the other variables (all $p \geq 0.075$, see Table 3 for details). However, post hoc tests revealed no significant difference between the three age groups across both task conditions (all $p \geq 0.076$). As expected, there was a significant effect of experimental condition for all variables (all $p \leq 0.001$, see Table 3 for details) except for variable error ($p = 0.981$), showing superior performance in the Direct condition relative to the Decoupled condition. More importantly, ANOVA revealed a significant interaction effect of group x condition for reaction time ($F_{(2,59)} = 7.553$, $p = 0.001$, $\eta^2 = .204$), initial movement time ($F_{(2,59)} = 4.681$, $p = 0.013$, $\eta^2 = .137$), total movement time ($F_{(2,59)} = 5.722$, $p = 0.005$, $\eta^2 = .162$), and corrective movement time ($F_{(2,59)} = 3.258$, $p = 0.045$, $\eta^2 = .099$). Post hoc analysis confirmed a significant difference between young children and adolescents in the Decoupled condition for reaction time ($p = 0.005$), total movement time ($p = 0.017$), and corrective movement

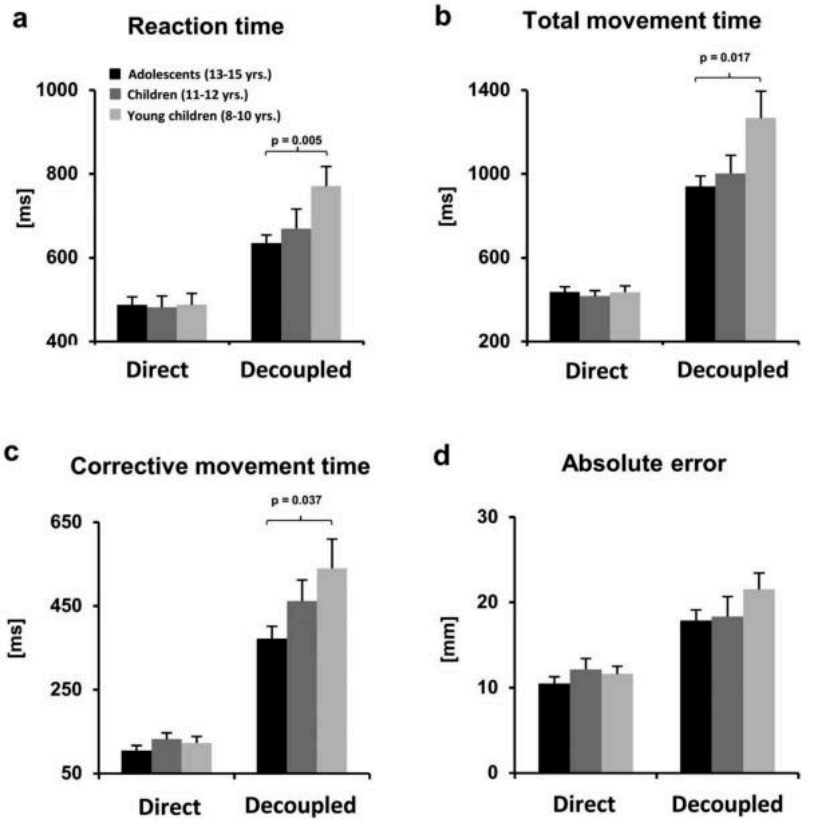

Figure 3. Mean (a) reaction time, (b) total movement time, (c) corrective movement time, and (d) absolute error for young children, children, and adolescents in both task conditions (Direct, Decoupled). Note the significant performance difference between young children and adolescents movement planning and timing but not movement execution in the Decoupled condition. In contrast, note no performance differences between young children, children and adolescents in the Direct condition. Bars represent the mean and standard error of the mean.

time ($p = 0.037$), but no differences between children and adolescents for these variables (all $p \geq 0.087$, see Table 3 for details) (cf., Figure 3(a–c)).

Taken together, reaction time, total movement time and corrective movement time were slower or longer in young children than in adolescents in the Decoupled condition but not in the Direct condition. In contrast, movement execution was similar between young children, children, and adolescents, in both conditions.

Discussion

The aim of the present study was to investigate the rate of rule-based eye-hand coordination development in children and adolescents. We were particularly interested in when the ability to integrate a rule-based element of cognition into a required motor action develops, and we examined this issue using two different visuomotor tasks. Participants performed a direct interaction task, where vision and hand action were

in spatial alignment and a non-standard visuomotor mapping task where the guiding visual information was decoupled from both the spatial plane in which hand movements were made and the direction of hand movements. Visuomotor performance of children and adolescents was then correlated with age in both visuomotor task conditions (i.e., with and without rule-based eye-hand-decoupling) and was also compared across different age groups. In accordance with our hypothesis, we found effects of age on visuomotor performance in the eye-hand-decoupled condition but not in the direct interaction condition. In addition, we found performance differences between young children and adolescents in the eye-hand-decoupled task and a peak in the eye-hand-decoupling development rate during late childhood. This peak may have led to the faster rule-based motor performance in early adolescence relative to young children.

In the eye-hand-decoupled condition, we observed significant relationships between age and movement planning and also between age and movement timing. Interestingly, larger correlations with movement planning (i.e., reaction time) were observed than with movement timing (e.g., total movement time). We did not observe a relationship between age and any of the movement execution variables (i.e., path length, absolute error, variable error). There were also no significant effects found for the direct interaction condition (cf. Figure 2(a–c)). Others have observed that there is a gradation of involvement of premotor cortical areas and primary motor cortex in going from movement preparation to movement execution, and well-known distinctions in terms of trajectory versus timing control in cortical versus subcortical brain regions (Georgopoulos, 2000; Hudspeth, Jessell, Kandel, Schwartz, & Siegelbaum, 2013; Shen & Alexander, 1997). Given the importance of premotor and prefrontal regions in eye-hand decoupling, one might speculate that with the introduction of spatial and cognitive rules, later premotor and prefrontal cortex development may reduce information processing speeds for communication with primary cortical and sub-cortical regions (Goldman-Rakic, 1987; Diamond, 2000). Such a developmental timeline may explain the relative performance differences we observed in movement planning and timing parameters between younger children and adolescents.

In the present study, the amount of direction reversals (i.e., the inhibition of the intuitive movement direction toward the visual target) was not affected by age in the rule-based eye-hand-decoupled task. This finding may be unexpected since executive functions linked to response inhibition are known to peak between 10 and 13 years (Paus, 2005). A possible explanation may be that the cognitive-spatial inhibition required in the eye-hand decoupled condition utilizes neural resources that differ from those required for purely cognitive executive function (e.g., during the Stroop color interference task) (Egner & Hirsch, 2005; Gorbet & Sergio, 2019). It could also be that the development of cognitive-spatial inhibition goes beyond the tested age ranges in the present cross-sectional study but would potentially be detected in a longitudinal study design and/or with a larger age range than 8–15 years. Others have observed that reaching to and grasping stationary targets in a task that required a plane change did not differ between 8 to 10-year-olds and adults (Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002). This finding suggests that including a feedback reversal in addition to a plane change in the current study may have increased the sensitivity of our measures to detect age-related differences. A future study including a plane change only condition and a feedback reversal only condition (Brown et al., 2015;

Hawkins & Sergio, 2014) could be helpful in elucidating the interplay between these different levels of visual-motor dissociation and developmental changes.

The main results of our study linked to eye-hand-decoupling were not affected by sex. We found sex differences of movement speed only in the direct interaction condition, an effect that was also independent of age. Sex-related differences between boy's and girl's eye-hand coordination have been widely reported in other studies, often linked to direct interaction tasks, such as catching and throwing (Wicks, Telford, Cunningham, Semple, & Telford, 2015). Thus, our findings of sex differences in the direct interaction condition seem to be consistent with the results of others. The lack of sex-related differences in our eye-hand decoupled condition suggests that the relationships between visuomotor mapping, development, and the sex of an individual require further examination.

It is well-known that youth typically increase time spent using a computer in adolescence (Cain & Gradisar, 2010; Hale & Guan, 2015). One might argue that the changes linked to eye-hand-decoupled development we observed in adolescents relative to young children could in part be related to increased computer use. However, we suggest that the age-related effects on eye-hand-decoupling are unlikely to be entirely dependent on computer usage. While regular computer use does include a plane change (i.e., eyes on a vertical monitor with hand responses made on a horizontal surface using a mouse or touchpad), the feedback reversal component of our task is not typically associated with computer use and was therefore novel for participants of all ages. Further, the performance boosts we observed appeared in late childhood, i.e., before the reported increase in computer use in adolescence. We also collected information about video game experience and self-reported skill level in our questionnaires but did not find a significant relationship between age and video game experience, nor a difference of video game experience or self-reported skill level between young children, children, and adolescents. This might provide further evidence that the reported age-related effects on eye-hand decoupling were not entirely based on increased computer use.

Neurological developmental differences between children and adolescents may be a more likely explanation for the observation that performance differed in children and adolescents in the eye-hand-decoupled task but not in the direct interaction task. Based on previous animal, human, and imaging studies (Gorbet & Sergio, 2016; Hawkins et al., 2013; Sayegh et al., 2014), we speculate that the eye-hand-decoupling development in youth may be concurrent with the strengthening of connections between the prefrontal, frontal, and parietal regions of the brain. This network connects the dorsolateral and rostral prefrontal cortex with visuomotor planning areas such as the supplementary motor area (SMA), dorsal premotor area (PMd), and superior parietal lobule (SPL) via white matter tracts. It is well-known that this network heavily contributes to the successful performance of rule-based eye-hand coordination (Gorbet & Sergio, 2016; Gorbet et al., 2004; Sayegh et al., 2014). Further, these areas are less developed in children compared to adolescents (Giedd & Rapoport, 2010; Paus, 2005). In particular, the rostral prefrontal cortex (rPFC, encompassing BA 10), which is active during eye-hand-decoupled tasks (Gorbet & Sergio, 2016) and also linked to multitasking and visuospatial short-term memory (Scherf, Sweeney, & Luna, 2006), is known to develop slowly throughout childhood and adolescence (Dumontheil, 2014; Dumontheil, Burgess, & Blakemore, 2008). Specifically, there is evidence that white matter density and directionality both increase from childhood to late adolescence (6–19 years old, Barnea-Goraly et al., 2005), a time period that is quite prolonged relative to primary sensory and

motor areas required for direct interaction tasks (Dumontheil et al., 2008). A similarly prolonged increase in dendritic arborization has been shown for the rPFC, with a concurrent reduction in grey matter volume. Notably, grey matter volume peaks between 11 and 13 years of age then decreases throughout adolescence (Giedd, 1999; Giedd & Rapoport, 2010) due to pruning and/or increased myelination. Hence, this region and its connectivity to cortical and sub-cortical behavioral control areas may represent a developmental "bottleneck" in terms of cognitive processes needed for eye-hand-decoupled performance. We, therefore, speculate that the development of frontoparietal network connections and frontal grey matter in areas linked to higher-order cognition may be responsible for the observed planning and timing related performance changes between children and adolescents in eye-hand-decoupling but not in the direct interaction task condition. Further study using brain imaging will be needed to confirm these ideas.

Future work is necessary to address further aspects of functional, rule-based motor development that were beyond the scope of the current study. A sample size of 62 is generally a good size for motor psychophysical research. However, because we were also interested in the effects of age and sex on behavior, the sub-group sizes and the small number of participants for a few ages can be considered as a limitation. Further, to comprehensively examine eye-hand-decoupled development, use of behavioral measures and brain imaging together in a longitudinal study design (Barnea-Goraly et al., 2005; Paus, 2005; Wicks et al., 2015), while logistically difficult, would prove highly useful to confirm the present results and would provide better insight into the underlying developmental mechanisms. Finally, an expansion of the age ranges, in general, would provide a more complete picture of eye-hand-decoupled development. It would be of interest to scrutinize whether eye-hand-decoupling further develops into young adulthood (cf. Figure 2(b), right graph), or if it instead levels off in adolescence (cf., Figure 2(a) right graph), and ideally also when it begins to decline with aging. To this end, we have previously observed a relationship between behavioral changes and white matter tract integrity in frontoparietal networks in elderly participants at risk for developing dementia (Hawkins, Goyal, & Sergio, 2015), but it is not known when this decline typically begins. Based on previous lifespan motor development studies (Leversen, Haga, & Sigmundsson, 2012), a U-shaped eye-hand-decoupling development function may be expected across the lifespan. One might argue that the first half of this U-shaped function comprises the results presented here, at least for movement planning (cf., Figure 2(a)). The eye-hand-decoupled task in combination with the direct interaction task used in the present study has been proven to be an effective and sensitive assessment tool in detecting performance declines in neurological disorder populations, e.g., in participants with high Alzheimer's risk, mild cognitive impairment, and a history of concussion (Brown et al., 2015; Hawkins & Sergio, 2014; Salek et al., 2011). Therefore, the present task might be able to provide timely knowledge about potential developmental delays and dysfunction and issues related to complex eye-hand coordination performance in youth populations (Piek et al., 2006).

In conclusion, the present study provides novel insight into the behavioral consequences of decoupling vision from motor action throughout childhood and adolescence and quantifies an important milestone of rule-based eye-hand-decoupled development. We observed eye-hand-decoupled performance differences between children and adolescents in the absence of differences in a direct interaction task where vision and motor action were in alignment. The ability to decouple vision from hand action differed between young children and adolescents

and emerged mainly during late childhood. The results of the present study suggest that the rate of cognitive development may present a constraint on the development of the ability to decouple vision from motor action, rather than visuomotor coordination development itself. We further suggest that the eye-hand-decoupled task used here could be a useful approach to comprehensively assess rule-based visuomotor transformation development.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Ethical conduct of research

The authors state that they have obtained appropriate institutional review board approval and have followed the principles outlined in the Declaration of Helsinki for all human or animal experimental investigations. In addition, for the investigation involving human subjects, informed consent has been obtained from the participants involved.

Data availability statement

The data set including demographic information from all participants and all variables of interest is available in the supplementary file "Data set".

References

Adolph, K. E., & Franchak, J. M. (2017). The development of motor behavior. *Wiley Interdisciplinary Reviews: Cognitive Science*, *8*(1–2), e1430.

Albines, D., Granek, J. A., Gorbet, D. J., & Sergio, L. E. (2016). Bimanual coordination development is enhanced in young females and experienced athletes. *Journal of Motor Learning and Development*, *4*(2), 274–286.

Barnea-Goraly, N., Menon, V., Eckert, M., Tamm, L., Bammer, R., Karchemskiy, A., … Reiss, A. L. (2005). White matter development during childhood and adolescence: A cross-sectional diffusion tensor imaging study. *Cerebral Cortex*, *15*(12), 1848–1854.

Brown, J. A., Dalecki, M., Hughes, C., Macpherson, A. K., & Sergio, L. E. (2015). Cognitive-motor integration deficits in young adult athletes following concussion. *BMC Sports Science, Medicine and Rehabilitation*, *7*, 25.

Cain, N., & Gradisar, M. (2010). Electronic media use and sleep in school-aged children and adolescents: A review. *Sleep Medicine*, *11*(8), 735–742.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development*, *71*(1), 44–56.
Dumontheil, I. (2014). Development of abstract thinking during childhood and adolescence: The role of rostrolateral prefrontal cortex. *Developmental Cognitive Neuroscience*, *10*, 57–76.
Dumontheil, I., Burgess, P. W., & Blakemore, S. J. (2008). Development of rostral prefrontal cortex and cognitive and behavioural disorders. *Developmental Medicine & Child Neurology*, *50*(3), 168–181.
Egner, T., & Hirsch, J. (2005). The neural correlates and functional integration of cognitive control in a Stroop task. *Neuroimage*, *24*(2), 539–547.
Georgopoulos, A. P. (2000). Neural aspects of cognitive motor control. *Current Opinion in Neurobiology*, *10*(2), 238–241.
Giedd, J. N. (1999). Brain development during childhood and adolescence: A longitudinal MRI study. *Nature Neurosci*, *2*(10), 861–863.
Giedd, J. N., & Rapoport, J. L. (2010). Structural MRI of pediatric brain development: What have we learned and where are we going? *Neuron*, *67*, 728–734.
Goldman-Rakic, P. S. (1987). Development of cortical circuitry and cognitive function. *Child development*, 601–622.
Gorbet, D. J., & Sergio, L. E. (2009). The behavioural consequences of dissociating the spatial directions of eye and arm movements. *Brain Research*, *1284*, 77–88.
Gorbet, D. J., & Sergio, L. E. (2016). Don't watch where you're going: The neural correlates of decoupling eye and arm movements. *Behavioural Brain Research*, *298*(Pt B), 229–240.
Gorbet, D. J., & Sergio, L. E. (2019). Looking up while reaching out: The neural correlates of making eye and arm movements in different spatial planes. *Experimental Brain Research*, 237(1): 1–14.
Gorbet, D. J., Staines, W. R., & Sergio, L. E. (2004). Brain mechanisms for preparing increasingly complex sensory to motor transformations. *Neuroimage*, *23*(3), 1100–1111.
Hale, L., & Guan, S. (2015). Screen time and sleep among school-aged children and adolescents: A systematic literature review. *Sleep Medicine Reviews*, *21*, 50–58.
Hawkins, K. M., Goyal, A. I., & Sergio, L. E. (2015). Diffusion tensor imaging correlates of cognitive-motor decline in normal aging and increased Alzheimer's disease risk. *Journal of Alzheimer's Disease*, *44*(3), 867–878.
Hawkins, K. M., Sayegh, P., Yan, X., Crawford, J. D., & Sergio, L. E. (2013). Neural activity in superior parietal cortex during rule-based visual-motor transformations. *Journal of Cognitive Neuroscience*, *25*(3), 436–454.
Hawkins, K. M., & Sergio, L. E. (2014). Visuomotor impairments in older adults at increased Alzheimer's disease risk. *Journal of Alzheimer's Disease*, *42*(2), 607–621.
Hudspeth, A. J., Jessell, T. M., Kandel, E. R., Schwartz, J. H., & Siegelbaum, S. A. (2013). *Principles of neural science*. McGraw-Hill, Health Professions Division, New York.
Leversen, J. S., Haga, M., & Sigmundsson, H. (2012). From children to adults: Motor performance across the life-span. *PloS one*, *7*(6), e38830.
Lubans, D. R., Morgan, P. J., Cliff, D. P., Barnett, L. M., & Okely, A. D. (2010). Fundamental movement skills in children and adolescents. *Sports Medicine*, *40*(12), 1019–1035.
Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinbourgh inventory. *Neuropsychologia*, *9*, 97–113.
Pangelinan, M. M., Zhang, G., VanMeter, J. W., Clark, J. E., Hatfield, B. D., & Haufler, A. J. (2011). Beyond age and gender: Relationships between cortical and subcortical brain volume and cognitive-motor abilities in school-age children. *Neuroimage*, *54*(4), 3093–3100.
Paus, T. (2005). Mapping brain maturation and cognitive development during adolescence. *Trends in Cognitive Sciences*, *9*(2), 60–68.
Paus, T. (2010). Growth of white matter in the adolescent brain: Myelin or axon? *Brain and Cognition*, *72*(1), 26–35.
Paus, T., Zijdenbos, A., Worsley, K., Collins, D. L., Blumenthal, J., Giedd, J. N., … Evans, A. C. (1999). Structural maturation of neural pathways in children and adolescents: In vivo study. *Science*, *283*(5409), 1908–1911.

Piek, J. P., Baynam, G. B., & Barrett, N. C. (2006). The relationship between fine and gross motor ability, self-perceptions and self-worth in children and adolescents. *Human Movement Science*, *25*(1), 65–75.

Salek, Y., Anderson, N. D., & Sergio, L. (2011). Mild cognitive impairment is associated with impaired visual-motor planning when visual stimuli and actions are incongruent. *European Neurology*, *66*(5), 283–293.

Sayegh, P. F., Hawkins, K. M., Neagu, B., Crawford, J. D., Hoffman, K. L., & Sergio, L. E. (2014). Decoupling the actions of the eyes from the hand alters beta and gamma synchrony within SPL. *Journal of Neurophysiology*, *111*(11), 2210–2221.

Scherf, K. S., Sweeney, J. A., & Luna, B. (2006). Brain basis of developmental change in visuospatial working memory. *Journal of Cognitive Neuroscience*, *18*(7), 1045–1058.

Schmithorst, V. J., Wilke, M., Dardzinski, B. J., & Holland, S. K. (2002). Correlation of white matter diffusivity and anisotropy with age during childhood and adolescence: A cross-sectional diffusion-tensor MR imaging study. *Radiology*, *222*(1), 212–218.

Schneiberg, S., Sveistrup, H., McFadyen, B., McKinley, P., & Levin, M. F. (2002). The development of coordination for reach-to-grasp movements in children. *Experimental Brain Research*, *146*(2), 142–154.

Shen, L., & Alexander, G. E. (1997). Preferential representation of instructed target location versus limb trajectory in dorsal premotor area. *Journal of Neurophysiology*, *77*, 1195–1212.

van der Fels, I. M. J., Te Wierike, S. C. M., Hartman, E., Elferink-Gemser, M. T., Smith, J., & Visscher, C. (2015). The relationship between motor skills and cognitive skills in 4–16 year old typically developing children: A systematic review. *Journal of Science and Medicine in Sport*, *18*(6), 697–703.

Wicks, L. J., Telford, R. M., Cunningham, R. B., Semple, S. J., & Telford, R. D. (2015). Longitudinal patterns of change in eye–Hand coordination in children aged 8–16 years. *Human Movement Science*, *43*, 61–66.