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Associations Between Object Control Skills and Cognitive Functions in Boys, Younger and Older Men: Across-Sectional Study

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ABSTRACT

Purpose: This study aimed to explore the association of cognitive function and process- as well product-oriented outcomes of object control skills (OCS) in boys, younger and older men. **Methods:** A total of 77 male participants took part in this study, including 35 primary school children (9.04 ± 0.53 years), 22 younger adults (23.5 ± 2.34 years), and 20 older adults (69.5 ± 4.43 years). We assessed the process-oriented performance of throwing, kicking, and catching performance using the component approach. For the product-oriented performance, throwing and kicking velocity was recorded with a STALKER SOLO 2.0 radar gun. For catching, the number of caught balls was assessed. Cognitive function was evaluated using the Trail-Making-Test (TMT) one day later. **Results:** Younger adults performed better in both domains than the other two groups. The results of the children and older adults were comparable in the motor and cognitive domains. However, the older adults yielded significantly better results for the process-oriented catching and product-oriented throwing performances. Moderate to strong correlations exist between OCS- and TMT performance, with significant correlations predominantly between product-oriented OCS results and TMT in children. **Conclusion:** The results of both domains support a hypothetical lifespan developmental trajectory with a progression from childhood to younger adult age and a degression in older adults. Furthermore, our results suggest that the suspected relationship between motor and cognitive function depends on age, the analyzed cognitive and motor skills, and the applied methodological approach (process-oriented vs. product-oriented).

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It has long been assumed that motor skills[1] and cognitive functions[2] were separate domains with independent underlying neurological processes and activated brain structures (Diamond, 2000). However, cognition is built from action and perception, thus making use of the motor system and perceptual functions (Jeannerod, 2006). Conversely, cognitive processes can support decision-making, motor control, and learning processes of motor skills (Raab & Green, 2005). Several hypotheses and models have been advanced to explain the neural and behavioral relationships of motor and cognitive performance, specifically for certain age groups or across the lifespan The continuously changing motor repertoire offers infants and children new opportunities to actively explore their physical and social environment through ongoing perceptual-action processes, supporting further cognitive development. In line with the embodied cognition approach, the continuous development of cognitive skills enables the acquisition of more diverse and complex motor skills (Adolph & Hoch, 2019). Consistent with these modeling ideas, recent neuroscience, and human movement science advances have revealed compelling links between motor and cognitive development, showing that many tasks require the parallel activation of cognitive-motor circuits, including the prefrontal cortex, striatum, and cerebellum, and that not only the prefrontal cortex can influence motor control, but that the cerebellum can also be important for cognitive function (Diamond, 2000; Leisman et al., 2014; Leisman et al., 2016). For example, motor and language network connectivity patterns overlap, implicating their overarching contribution to each other's and higher cognitive development (Bruchhage et al., 2020).

Cognitive and motor functions show similar trajectories during development, are acquired in similar ways, show similar learning stages, and have related training effects (Rosenbaum et al., 2001; van der Fels et al., 2015); for example, gross motor skill development in infants and toddlers is predictive of future cognitive outcomes (Marrus et al., 2018). Moreover, when cognitive development is disturbed (e.g., in children with Down Syndrome, Autism spectrum disorders, ADHD, Developmental Coordination Disorder), motor development is often also impaired (Fulceri et al., 2019; Kaiser et al., 2015; Schott & Holfelder, 2015). The concept of reciprocity and the theory of automaticity describe the trajectories of motor and cognitive development (McClelland & Cameron,

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[1]Motor skills are defined as a task group or class of purposeful and deliberate movements with comparable sequences and functions that can be modified through training, experience, and reinforcement. Elementary motor skills are divided into skills for locomotion (including walking, running, hopping, jumping) and object control (e.g., throwing, catching, shooting) (Holfelder & Schott, 2014).

[2]The term cognition refers to all conscious and unconscious information-processing processes of an intelligent system or the mental activity of a human being. The cognitive performance of a human being includes processes of perception, attention, memory, thinking, learning, remembering, motivation and problem solving as well as language comprehension.

2019). Reciprocity occurs when skills develop and improve in parallel. The theory of automaticity states that the performance of motor and cognitive tasks compete for the same attentional resources (see Gandotra et al., 2021, for a detailed discussion).

Many studies are available on the relationship between fitness and cognition at individual life stages (Clouston et al., 2013; Rigdon & Loprinzi, 2019; St Laurent et al., 2021), but few studies focus on the relationship between motor skills and cognitive functions (Gandotra et al., 2021; van der Fels et al., 2015). In their recent systematic review, van der Fels et al. (2015) summarized the results of eight articles on the relationship between object control skills (OCS) and various aspects of cognitive abilities (including intelligence, working memory, executive functions, attention) in typically developing children and adolescents between 4 and 16 years of age. They found weak correlations between OCS and visuo-spatial working memory and fluid intelligence. Furthermore, there was insufficient evidence for the relationship between OCS and EF, attention, verbal comprehension, and academic ability. In addition, they found that the association between cognitive and motor skills appeared to decrease in children older than 13 years of age, which may be due to age-related brain differentiation, a phenomenon whereby brain functions that are localized to specific, distinct, and differentiated brain areas in adolescents and young adults become less so as people growing older. A recent study by van der Fels et al. (2019) found significant correlations between gross motor skills and response inhibition but not for interference control in $n =$ 732 children of grades 3 and 4. However, no results specific to individual OCS were reported. In another study of $n = 89$ children aged 10–12 years, weak to moderate relationships between executive functions (EF) and OCS were found (Ludyga et al., 2018). As a reason for the inconsistent results, van der Fels et al. (2019) suggest that varying degrees of cognitive abilities are related to gross motor skills. Gandotra et al. (2021) found positive but non-significant correlations for the relationship between OCS and the EF components of working memory, inhibition, and cognitive flexibility in 4866 children aged 3 to 12 years. According to the authors, these skills are largely automatic in children and require minimal higher-level cognitive input. This could be the case because OCS are frequent in school sports (starting from grade 5); therefore, children are increasingly familiar with them and practice them extensively. From the perspective of sports in which OCS are used, some studies suggest that athletes from sports with predominantly open skills (e.g., soccer, team handball, tennis) perform better on tests of EF (Huijgen et al., 2015; Verburgh et al., 2014; but see also Holfelder et al., 2020). These findings can be explained by the high cognitive demands of performing open skills in a functional ecological context (e.g., soccer game) and the assumption that athletes from open-skill sports are constantly confronted with these cognitive stimuli.

In younger as well as older adults, our literature search did not reveal any studies on the relationship between object control and cognitive performance. In these life stages, the relationship between locomotion and cognition has mostly been examined using the dual-task paradigm (Peel et al., 2019; Smith et al., 2017). For example, Nóbrega-Sousa et al. (2020) found that better gait performance was associated with lower oxygenation in the prefrontal cortex and better EF in individuals aged 30–70 years, but with only "weak" coefficients ($r = 0.2–0.4$). However, it is important to remember that in locomotor tasks, well-learned skills are used that require little cognitive control (especially in young adults), especially EF and attention (Yogev-Seligmann et al., 2008). On the other hand, if an individual needs to focus on a specific movement feature or the entire movement in a task to successfully perform the motor task (e.g., when learning a new task, when confronted with new or changing situational conditions, such as in ball games, or when performing a challenging/complex task), then cognitive control processes become necessary to a greater extent (Poldrack et al., 2005). In summary, the presented findings from neuroimaging studies and behavioral studies lead to the assumption that a positive relationship exists between motor and cognitive performance across the lifespan.

The studies included in the meta-analysis by van der Fels et al. (2015) and Gandotra et al. (2021) only partially accounted for confounding variables such as socioeconomic status, body mass index, or sex differences in object control were found for 3 to 6-year-olds (Zheng et al., 2022), but no differences in catching and kicking were found for children and adolescents aged 5 to 14 years (Butterfield et al., 2012). Significant sex differences were shown in throwing velocity for young and older adults but not for the qualitative execution parameters (Lorson et al., 2013). In a recent review, Grissom and Reyes (2019) showed that while individual factors may show a tendency toward sex bias across the lifespan (e.g., increased impulsive action in males, decreased reaction time in males, improved working memory in females), the sex differences in EF are small. Another meta-analysis has shown that there is no sex difference in adults in any of the three domains of performance monitoring (ability to monitor for adverse or unexpected outcomes within tasks, including conflict between possible options, the commission of errors, and updating ones working memory), response inhibition (ability to suppress task-irrelevant behaviors, thereby strengthening task-relevant behaviors to enable goal-directed behavior), or cognitive set-shifting (ability to switch between mental sets depending on task requirements using working memory) (Gaillard et al., 2020). However, the authors did find task-specific sex differences with significantly better results in females for response inhibition (Delay Discounting task) and significantly better results in males performing the CANTAB Spatial Working Memory task.

The present study

While these previous studies have contributed to the understanding of the relationship between motor skills and cognitive control, none has examined the relationship between object control (process-oriented: quality of movement, e.g., component analysis and product-oriented: outcome of the movement, e.g., throwing speed) and cognitive function simultaneously in children, younger adults, and older adults. Since experience with ball sports have a strong influence on the development and maintenance of OCS, and since women were not allowed to play soccer actively in Germany until 1970, and since there are almost no "old ladies' teams", we decided to investigate "only" men for this first life span oriented study. Therefore, building on previous studies, the current study aimed to examine how different OCS (i.e., throwing, catching, kicking) are related to different components of cognitive control (working memory, inhibition, cognitive flexibility). We expected a positive correlation between motor and cognitive outcomes, i.e., that good object control is associated with better cognitive performance (especially in terms of EF) with an U-shaped pattern across this study's three different age groups. We predicted that correlations should be higher in the children's and older adults groups than in the younger adults' group because cognitive and motor performance change more in children and older adults; motor control needs a higher degree of cognitive control in these age groups due to a lower level of automatization in children and increasing personal constraints with age (Northey et al., 2018; van der Fels et al., 2015).

Methods

Participants

Of the overall 120 male participants tested for OCS performance (Holfelder & Schott, 2021), 79 male participants between the ages of 8 and 79 years were asked to additionally perform the Trail-Making-Test (TMT; Reitan, 1958). The other 41 participants, 1st and 2nd-grade children, were excluded because the TMT is too difficult for children at this age. In addition, data sets were excluded due to missing cognitive scores from two of the 79 participants, so data from 77 individuals were included in the analyses. The sample was divided into three age groups: 1) Children of the 3rd and 4th grade (8–10 years, $n = 35$); 2) Younger adults (YA, 20–27 years, $n = 22$), and 3) Older adults (OA, 62–79 years, $n = 20$). We selected these age groups to reflect best the changes across the lifespan. The age range of 8 to 10 reflects an age when the selected skills are still developing. Younger adults were chosen to represent an age at which performance can be achieved at a very high level (as a benchmark, so to speak). Older adults have the most extensive movement experience, but are characterized by an age-related decline in physical performance.

Participants were voluntarily recruited from a middle-class social area and were blinded to the purpose of the experiment. Informed written consent was obtained before the beginning of testing. Written informed consent was also obtained from their parent or guardian for children recruited from a regional elementary school. Participants were informed that they could opt-out at any time. All procedures were in accordance with the Declaration of Helsinki (2013), with ethical standards, legal requirements, and international norms. The institutional ethics committee approved the project (approval number: AZ 22-003).

Test items and materials

Cognitive performance was assessed using the Trail-Making-Test (TMT; Reitan, 1958). Both process- and product-oriented measures of OCS were evaluated for the three different skills of throwing, kicking, and catching.

Cognitive performance

The original Paper Pencil version of the TMT (Reitan, 1958) consists of two subtasks. TMT-A consists of 25 numbered circles that are to be connected in ascending order (e.g., 1-2-3). This part assesses visuo-perceptual abilities and motor processing speed. In the second part (TMT-B), 25 circles alternating between numbers and letters are connected in ascending but alternating sequences (1-A-2-B-3-C). Here, additional cognitive flexibility (set-shifting, inhibition), working memory performance, and divided attention are assessed (Linari et al., 2022; Salthouse, 2011). The time to complete TMT-A and TMT-B and the number of errors were recorded as performance indicators. Due to the longer overall trail length of TMT-B compared to TMT-A and TMT-motor speed, we report the speed (cm/s) instead of the total duration (Schott & Klotzbier, 2018). The TMT was chosen because it is one of the most popular tests for EF assessment, has a short administration time, and is easy to understand (Linari et al., 2022; Salthouse, 2011). Furthermore, the cognitive abilities covered by the TMT are highly relevant in sports (e.g., team handball, soccer, basketball) where the OCS tested in this study are applied. A weakness of the TMT is the low specificity in discriminating between the different cognitive processes assessed.

The TMT was conducted one day after the assessment of the OCS. Test-retest reliability is high for the TMT; further, the TMT correlates with intelligence tests, concentration, and visuospatial tests, among others (Bowie & Harvey, 2006).

Object control skill assessment. For the product-oriented assessment, ball velocity during throwing and kicking was defined as the peak velocity measured with a radar gun (SOLO 2.0, STALKER, USA; unit: m/s) after release or hit by hand or foot. This method has been commonly used in standard field measurements (Weisberg et al., 2020). The manufacturer calibrated the radar gun with a maximum root-mean-squared error of 1.906 km/h. Peak ball velocity of throwing and kicking was recorded for each trial, as was the number/percentage of balls successfully caught. For the OCS throwing and catching, age-appropriate balls were used according to the International Handball Federation (IHF) guidelines, for kicking Fédération Internationale de Football Association (FIFA) approved balls. Each participant performed five (children) or ten (younger and older adults) trials of each OCS. Participants were instructed to throw or kick as hard as possible against the target. In throwing, a 0.5 × 0.5 m target was fixed on the middle of a mat starting 100 cm above the floor level. The throwing distance was defined depending on the body height [4 m with a height ≤120 cm; 4.5 m with a height 120–140 cm or 5 m with a height ≥140 cm]. In kicking, seven meters before the ball (for all age groups), a 1.5 × 1.5 m target was fixed on the middle of a mat starting 20 cm above the floor level. The approach run-up for kicking was standardized to one step. For throwing and kicking, trials in which the mat (5 × 4 m) with the target was not hit were counted but not analyzed. In catching, the participants had to produce a two-handed catch when a ball was manually thrown from a distance of 6 m toward the catcher. A successful catch was scored with 1 point.

We evaluated OCS patterns using component developmental sequences for the overarm throw and kicking for force and catching for process-oriented assessment (modified from Roberton & Halverson, 1984; Strohmeyer et al., 1991) as well as a modified version for kicking for force (Bloomfield et al., 1979; Holfelder & Schott, 2021; Holfelder et al., 2013; Mally et al., 2011). Catching comprises the three components *Arm action*, *hand action*, and *body action*, whereby a minimum of three and a maximum of ten points can be achieved. Throwing consists of the four components *Step action*, *Trunk action*, *Preparatory arm backswing*, and *Arm & hand action*, with a minimum of four and a maximum of 15 points. Kicking consists of the six components *Approach—support leg position in relation to the ball*, *Backswing of the kicking leg (thigh)*, *Backswing of the kicking leg (lower leg)*, *Ball contact*, *Upper trunk position during contact*, and *Arm action*. This results in a minimum value of six and a maximum value of 20 points.

During the throws and the kicks, the participants were video recorded (frequency of 100 Hz) by two cameras, during the catches by one. Based on the recorded videos, two investigators categorized each trial using the movement component analysis approach (Roberton & Halverson, 1984). A zero score was assigned if a participant did not perform the skill in a particular fashion (e.g., missed the target zone or performed a one-handed catch).

The single sequences of the movement components for catching, throwing, and kicking and the more detailed procedure of assessing the OCS are viewable in detail in Holfelder and Schott (2021). In addition, Logan et al. (2017) demonstrated the validity of developmental sequences following the component approach.

Other variables. For descriptive purposes, height was measured to the nearest 0.1 cm and body mass to the nearest 0.1 kg for all participants. The Body Mass Index (BMI) was calculated as mass (kg) divided by height (m^2). In order to determine the BMI categories (underweight, normal, or overweight) of an individual, depending on age and sex, we utilized German BMI percentiles for children and adolescents as well as adults (Hemmelmann et al., 2010; Kromeyer-Hauschild et al., 2001). Furthermore, participants were asked which organized activities (participation through a formal sports club) they had participated in over the past 12 months. Next, they were asked how many days a week and minutes per session they had participated in that particular activity. Total exercise (h/week) was calculated as follows: (frequency 1 × duration 1) + (frequency 2 × duration 2) + (frequency 3 × duration 3) (Schott et al., 2016).

Statistical analysis

All statistical analyses were performed with SPSS v.27 (SPSS, Chicago, IL). First, the dependent variables (process- and product-oriented OCS throwing, kicking, catching; TMT-A and TMT-B) were examined to check for missing data points, normality of distributions, the presence of outliers, assumption of linearity, and the homogeneity of variance. An alpha level of .05 was used for all statistical tests. Next, potential group differences for continuous variables (i.e., age, height, weight, BMI, product- and process-oriented results of OCS, TMT) were assessed using ANOVAs. To follow up on the main effects of age group, post-hoc tests (using Bonferroni-Holm correction) were performed. Pearson's bivariate correlations between demographic and anthropometric variables, TMT (TMT-A, TMT-B, and TMT ratio as (B-A)/A), process- and product-oriented measures of OCS were calculated separately by age group. Correlation coefficients are interpreted according to Cohen's (1992) magnitude of effect sizes (small: $r = .10$; medium: $r = .30$; large: $r = .50$).

We then used hierarchical multiple regression analyses to examine associations between process- and product-oriented OCS scores and cognitive domain scores (TMT-A, TMT-B) separately for each age group. Model 1 contained age and exercise; Model 2 added the cognitive domain scores. Only significant ($p < .05$) findings are reported.

Results

Sample characteristics

The demographic characteristics of all the participants are shown in Table 1. Of the sample, 6.5% were obese (11.4% children, 5.0% older adults); however, 10.4% were underweighted (5.7% children, 4.5% younger adults, 25% older adults). 41% of children are active for three hours or more per week; among younger adults, 82%, and among older adults, 50%.

Motor performance

The detailed results of the entire sample on motor performance are published elsewhere (Holfelder & Schott, 2021). For all components of the three OCS, intra- and inter-rater were good to excellent, according to the guidelines of Koo and Li (2016). In other words, the scores obtained by the same rater on different trials (throwing ICC .92–.97; kicking ICC .85–.97; catching ICC .75–.89) or by two different raters were comparable (throwing ICC .89–.99; kicking ICC .72–.99; catching ICC .88–.99).

Table 1. Sample characteristics. Group means, and standard deviations.

	Children 3rd & 4th grade $n = 35$	Younger Adults 20 to 27 years $n = 22$	Older adults 62 to 79 years $n = 20$
Age [years]	9.04 ± 0.60	23.5 ± 2.35	69.5 ± 4.43
Height [cm]	138 ± 7.50	184 ± 7.58	178 ± 5.63
Weight [kg]	31.99 ± 6.80	79.0 ± 7.35	82.1 ± 12.1
BMI [kg/m^2]	16.63 ± 2.19	23.5 ± 2.28	25.9 ± 3.62
Exercise (min/week)	177 ± 113	314 ± 147	317 ± 213

Catching

Univariate ANOVAs yielded significant effects of age group on process-oriented performance, $F(2,74) = 22.32$, $p < .001$, $\eta^2_p = .376$, but not on product-oriented performance, $F(2,74) = 0.015$, $p = .985$, $\eta^2_p = .000$. The post-hoc tests revealed, that, both younger and older adults scored significantly better than the children on the process-oriented measure ($p < .001$) (see Table 2). However, there were no significant differences in the product-oriented measure.

Throwing

Univariate ANOVAs revealed significant effects of age group on process-oriented performance, $F(2,74) = 6.68$, $p = .002$, $\eta^2_p = .153$, and on product-oriented performance, $F(2,74) = 56.87$, $p < .001$, $\eta^2_p = .606$. Post-hoc tests yielded significant differences between children and younger adults ($p = .003$) as well as between younger and older adults ($p = .013$) for the process-oriented measure, with better results for the younger adults in both cases (see Table 2). Younger adults scored better on the product-oriented measure than the other groups ($p < .001$). Older adults showed significantly better results on the product-oriented measure than the children ($p = .002$).

Kicking

Univariate ANOVAs yielded significant effects of age group on process-oriented performance, $F(2,74) = 16.04$, $p < .001$, $\eta^2_p = .302$, and on product-oriented performance, $F(2,74) = 51.57$, $p < .001$, $\eta^2_p = .582$. According to the post-hoc tests, younger adults performed better than both groups for the process-oriented measure ($p < .001$). Again, younger adults yielded better performances on the product-oriented measure than all other groups ($p < .001$) (see Table 2).

Cognitive performance

Univariate ANOVAs yielded significant effects of age group on TMT-A speed performance $F(2,74) = 32.77$, $p < .001$, $\eta^2_p = .470$, on TMT-B speed performance $F(2,74) = 38.64$, $p < .001$, $\eta^2_p = .511$ and TMT-B errors $F(2,74) = 4.819$, $p = .011$, $\eta^2_p = .115$. For the TMT ratio $F(2,74) = 1.955$, $p = .149$, $\eta^2_p = .050$ and TMT-A errors $F(2,74) = 0.481$, $p = .620$, $\eta^2_p = .013$, no significant main effects exist.

Post-hoc tests revealed for TMT-A and TMT-B speed performance, that younger adults showed significantly better results than all other groups ($p < .001$). Furthermore, younger adults made significantly fewer mistakes than children during the TMT-B ($p = .008$) (see Table 3).

Association between motor and cognitive performance per age group

Table 4 shows moderate to strong correlations between OCS- and TMT performance. Although no consistent pattern can be discerned, it is noticeable that significant correlations are predominantly between product-oriented OCS results and the TMT, predominantly in children. The only significant negative correlation exists for the relationship between product-oriented kicking performance and TMT-A speed for younger adults ($r = -.451$, $p = .035$).

The regression analyses on motor performance indicated overall significant effects with adjusted R^2 between .12 and .39, indicative of a moderate to high goodness-of-fit, according to Cohen (1988) (see Table 5). There were significant effects of age, exercise, and TMT-B on the product- and process measures of *catching*, indicating that better performance was associated with increasing age and greater exercise, especially in the group of children. In addition, our results suggest that TMT-B speed increased with increasing catching performance in children. The scores of the product-oriented measure for *throwing* were significantly predicted by the TMT-B in children, while the TMT-A predicted better performance in older adults. In both cases, better throwing performance was accompanied by better performance in TMT-A and TMT-B, respectively. Age, exercise, and TMT did not contribute to the process-oriented throwing regression models. The process-oriented measure

Table 2. Object control skill performance. Group means, and standard deviations.

	Children 3rd & 4th grade $n = 35$	Younger adults 20 to 27 years $n = 22$	Older adults 62 to 79 years $n = 20$
Catching process-oriented [score]	8.17 ± 1.47	10.00 ± 0.00	9.65 ± 9.33
Catching product-oriented [trials]	9.49 ± 1.12	9.50 ± 0.67	9.45 ± 0.94
Throwing process-oriented [score]	10.09 ± 2.31	12.41 ± 2.58	10.15 ± 2.72
Throwing product-oriented [m/s]	10.08 ± 1.54	15.79 ± 2.55	12.02 ± 1.91
Kicking process-oriented [score]	13.40 ± 1.83	15.91 ± 2.20	12.55 ± 2.21
Kicking product-oriented [m/s]	15.91 ± 1.90	21.77 ± 2.58	16.17 ± 2.45

Table 3. Trail-making-test performance. Group means, and standard deviations.

	Children 3rd & 4th grade $n = 35$	Younger adults 20 to 27 years $n = 22$	Older adults 62 to 79 years $n = 20$
TMT A [cm/s]	4.21 ± 1.12	7.69 ± 2.42	4.48 ± 1.42
TMT A [errors]	0.89 ± 1.11	0.64 ± 0.66	0.75 ± 0.91
TMT B [cm/s]	2.39 ± 0.63	5.06 ± 1.71	2.77 ± 1.12
TMT B [errors]	1.69 ± 1.41	0.55 ± 0.80	1.30 ± 1.69
TMT ratio (B-A)/A	−0.42 ± 0.14	−0.32 ± 0.21	−0.37 ± 0.22

Table 4. Intercorrelations Pearson's r (p) among cognitive and motor performance, age, height, weight, and exercise by age group.

	Children 3rd & 4th grade $n = 35$		Younger adults 20 to 27 years $n = 22$		Older adults 62 to 79 years $n = 20$	
	TMT A speed	TMT B speed	TMT A speed	TMT B speed	TMT A speed	TMT B speed
Age (years)	**.385 (.023)**	.250 (.147)	.027 (.904)	−.246 (.270)	−.368 (.111)	−.322 (.167)
Height (m)	**.515 (.002)**	**.348 (.041)**	−.288 (.194)	.002 (.992)	−.207 (.381)	.043 (.859)
Weight (kg)	**.411 (.016)**	**.411 (.016)**	−.153 (.495)	−.313 (.156)	.146 (.540)	−.026 (.914)
Exercise (min/week)	.197 (.297)	.218 (.248)	.030 (.895)	−.208 (.352)	−.191 (.420)	.109 (.648)
Catching process-oriented [score]	**.338 (.047)**	**.376 (.026)**	–	–	.094 (.694)	−.022 (.926)
Catching product-oriented [trials]	.074 (.671)	**.424 (.011)**	.076 (.737)	−.332 (.132)	.105 (.659)	−.021 (.929)
Throwing process-oriented [score]	.305 (.074)	.259 (.134)	−.025 (.912)	.238 (.286)	.287 (.219)	.245 (.298)
Throwing product-oriented [m/s]	**.425 (.011)**	**.397 (.018)**	−.117 (.605)	−.088 (.695)	**.595 (.006)**	.293 (.209)
Kicking process-oriented [score]	.082 (.638)	.152 (.383)	.148 (.512)	.194 (.386)	**.460 (.041)**	.157 (.508)
Kicking product-oriented [m/s]	**.518 (.001)**	**.449 (.007)**	**−.451 (.035)**	−.187 (.405)	.444 (.050)	.143 (.546)
TMT A speed [cm/s]	–	**.638 (<.001)**	–	**.545 (.009)**	–	**.647 (.002)**

Table 5. Results of the multiple regression analysis by object control skill per age group.

		t	*p*	*β*	*F*	*df*	*p*	*adj. R²*
Catching – process-oriented								
children	TMT B	2.28	.031	.396	5.19	1,28	.031	.126
Catching – product-oriented								
children	exercise	2.92	.007	.475	6.11	1,27	.007	.259
	age	2.40	.024	.390				
younger adults	exercise	2.91	.009	.546	8.48	1,20	.009	.263
Throwing – process-oriented								
	–	–	–	–	–	–	–	–
Throwing – product-oriented								
children	age	1.96	.060	.324	6.46	1,27	.028	.273
	TMT B	2.32	.028	.383				
older adults	TMT A	3.14	.006	.595	9.87	1,18	.006	.318
Kicking – process-oriented								
older adults	TMT A	2.20	.041	.460	4.83	1,18	.041	.168
Kicking – product-oriented								
children	age	1.78	.087	.292	7.19	1,26	.001	.390
	exercise	2.10	.046	.324				
	TMT A	2.41	.023	.397				
younger adults	TMT A	-2.26	.035	-.451	5.10	1,20	.035	.163

of *kicking* was significantly predicted by TMT-A, indicating that good kicking performance was significantly related to good TMT-A performance, particularly in the older adult group. Age, exercise, and TMT-A performance significantly contributed to the product measure of kicking, indicating that faster kicking speed was associated with increasing age, higher exercise duration, and faster TMT-A speed.

Discussion

The overall objective was to examine the associations between process- and product-oriented measures of three OCS (catching, throwing, and kicking) and cognitive performance (TMT) in boys and men across the lifespan.

Current research demonstrated that there is no uniform relationship between general (fundamental) motor skills and cognition (Cameron et al., 2016). Instead, there appear to be very specific interrelations depending on which aspect of EF and whether gross or fine motor skills are investigated (van der Fels et al., 2015). Our correlation analyses also reflect these findings, which do not show a clear pattern and provide unexpected results, such as the significant negative correlation of $r = -.451$ between kicking velocity and TMT-A speed in the younger adults' group.

According to the expected U-shaped pattern across this study's three different age groups, the most significant correlations were observed between OCS and TMT performance in children. This is particularly true for catching and the product-oriented results of throwing and kicking. These positive relationships between catching and TMT results in children are particularly interesting. The manipulative OCS catching can be categorized as a demanding movement that requires anticipation of flight speed, trajectory, and object size (Montagne et al., 1999). Successful catching, therefore, requires increased capacities of visual information processing (López-Moliner et al., 2010), cognitive functions which are also helpful for completing the TMT successfully (Karimpoor et al., 2017) and are still developing in primary school children (Wood et al., 2018). Compared to the other two investigated OCS, these previously mentioned requirements of increased capacities of visual information processing for successful catching (e.g. the anticipation of flight speed, trajectory, and object size) is also reflected in the results of the regression analyses by means of the significant effects of age, exercise, and the interaction of age x TMT-B on the product- and process-oriented measures of catching. Compared to the children, younger and older adults complete significantly more exercise per week, have significantly more overall movement experience due to their age, and their capacities of visual information processing are more developed (López-Moliner et al., 2010). While visual information processing is relevant to OCS throwing and kicking as well, or the sports in which these OCS are applied, visual information processing seems to be more pronounced for catching (movement of the object toward the body) than for throwing and kicking (movement of the object away from the body). A look at the further results of the regression analysis shows that TMT-B significantly predicted the product-oriented throwing performance. Information processing speed (TMT-A) is an important predictor for kicking in children and younger adults. While the significant results are consistent with the main research question, it is not directly apparent how the different results of TMT-A and TMT-B on the process- and product-oriented results in throwing and kicking occurred. All cognitive skills assessed by the TMT seem to be highly relevant for sports in which the OCS throwing and kicking are applied. A possible explanation could be that the TMT is not sufficiently sensitive to discriminate between the different cognitive skills (Linari et al., 2022).

In addition, the relationship between TMT performance and the product-oriented results of OCS throwing, kicking, and catching can be explained by the practical application in the respective sports (e.g., soccer and team handball). When performing these sports, both domains are practiced at the same time. The motor skills are continuously trained and improved, and one is constantly confronted with cognitive stimuli like attention, visuo-perceptual abilities, motor processing speed, cognitive flexibility, working memory, and inhibition (e.g., Huijgen et al., 2015; Holfelder et al., 2020), cognitive processes which are assessed with the TMT (Linari et al., 2022). Although a moderate to large relationship exists between product-oriented and process-oriented outcomes of OCS (Holfelder & Schott, 2021), we found more significant relationships between product-oriented results and TMT, particularly in the children group. Besides technical aspects and body composition, throwing and kicking velocity strongly depend on maximum and explosive strength. Physical exercise results in increased production of growth factors such as IGF-1 or BDNF (Gomez-Pinilla & Hillman, 2013), which not only have an important function in controlling exercise-induced muscle hypertrophy processes (Schoenfeld, 2013) but also have a positive influence on cognitive processes (Gómez-Pinilla & Hillman, 2013). Therefore, one possible explanation would be that in childhood, when muscle mass is increasingly built up, the influence of these mechanisms is more pronounced. However, the more pronounced relationships between cognitive and motor skills in the children group compared to the other groups are consistent with a practical implication of the review of van der Fels et al. (2015). They noted that the association of cognitive and motor skills appears to decrease in children older than 13 years due to a development of motor and cognitive skills in equal stages in pre-pubertal children, followed by a more separate development around the age of puberty (Anderson et al., 2001; van der Fels et al., 2015). This may also be the most understandable explanation for why the most significant associations between TMT and OCS were identified in the children's group. In addition, the children in this study have a relatively homogeneous age structure and are at an age when cognitive and motor skills are developing strongly (Morgan et al., 2013; van der Fels et al., 2015), so the motor and cognitive stimuli may lead to more substantial and more specific adaptations. In contrast, the two other groups have a wider age range, and a more differentiated motor and cognitive life course can be assumed. Furthermore, some varying correlations between OCS and TMT could result from the largely automated OCS, which require minimal higher-level cognitive input (Gandotra et al., 2021). This argument is in line with the explanation mentioned above by van der Fels et al. (2015) and seems related to our study, especially relevant to the results of the younger adults, who achieved the best results in both domains.

Nevertheless, particularly in older adults, one might have expected more apparent relationships along the lines "A healthy brain in a healthy body" (Douw et al., 2014), i.e., with the understanding that well-developed OCS and an assumed underlying higher level of physical activity level positively counteract the natural decline in cognitive performance with age (Northey et al., 2018). At least, this assumption is reflected in the regression analyses for the product- and process-measures of catching. The participants in the group of older adults may be too heterogeneous in terms of age, exercise level, and motor and cognitive performance, so that the expected relationship between motor and cognitive performance is only partly apparent. This impression tends to be shown in the descriptive results considering the coefficient of variation (quotient of standard deviation and mean). Jauny et al. (2022) report that the large variability of the natural decline in cognitive performance in older adults can be explained by, among other things, functional disorganization accompanied by increased variability in synchronized brain communication, connectivity dynamics, and information flow between different brain regions.

Although it provides some initial results on the specific relationship between different OCS and cognitive performance across the lifespan in males, some limitations should be mentioned. First, a longitudinal design instead of the cross-sectional one would also increase the informative value, making it possible to analyze developmental trajectories between motor and cognitive performance. Although the TMT assesses different executive processes, which were deliberately chosen for test ecological reasons, it covers only a range of cognitive performance, and the different executive processes are not well discriminated by this test (Linari et al., 2022). Therefore, further cognition tests that test other parts of cognitive performance relevant to sports practice would be of great interest to better understand which cognitive processes are related to OCS. Finally, no girls, women, and adolescents were tested so that no conclusions could be made about a potential gender gap. Therefore, these results can only be generalized for males in the age ranges investigated. Complementing the need for longitudinal studies, it would be interesting to additionally study adolescents and adults between the ages of 30 and 60 years to cover the entire life span. The study of women could also identify findings on possible sex differences for the relationship between OCS and cognitive performance.

What does this article add?

To our knowledge, the present study is the first to examine the relationships between process- and product-oriented aspects of catching, throwing, and kicking and cognitive performance (TMT) in three different age groups across the life span in males. In particular, the results of the OCS throwing and kicking and those of the TMT support the results of Lorson et al. (2013) for a hypothetical lifespan developmental trajectory. However, our results suggest that the suspected relationship between motor and cognitive performance depends on age, the analyzed cognitive and motor skills, and the applied methodological approach (process-oriented vs. product-oriented). Thus, general statements about this relationship are not yet possible. Although many aspects of internal validity were taken into account when conducting the study (e.g., attentional focus, verbal encouragement, feedback), other moderators and mediators in the analyses (e.g., lower and upper extremity strength, shoulder, hip, knee mobility) were not considered in this study. In the sense of ecological validity, motor assessments should also be used in future studies, which are less static but rather integrate the ball sports character. For this purpose, automatized methods using sensors will have to be developed in the future. Nevertheless, as a practical implication, there are tendencies that both domains seem to interact positively, which should be considered when planning physical activity regarding both the physiological and cognitive stimuli.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethics

Informed written consent was obtained prior to the beginning of testing. In the case of children (<18 yrs), additional informed written consent was also provided from their parent or guardian. Participants were told that they could opt out at any time. All procedures were in accordance to the Declaration of Helsinki (2013) with ethical standards, legal requirements and international norms. The institutional ethics committee of the University of Stuttgart (approval number: AZ 22-003) approved the project.

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References

Adolph, K. E., & Hoch, J. E. (2019). Motor development: Embodied, embedded, enculturated, and enabling. *Annual Review of Psychology*, *70*(1), 141–164. https://doi.org/10.1146/annurev-psych-010418-102836

Anderson, V. A., Anderson, P., Northam, E., Jacobs, R., & Catroppa, C. (2001). Development of executive functions through late childhood and adolescence in an Australian sample. *Developmental Neuropsychology*, *20*(1), 385–406. https://doi.org/10.1207/S15326942DN2001_5

Bloomfield, J., Elliott, B., & Davies, S. (1979). Development of the soccer kick: A cinematographical analysis. *Journal of Human Movement Studies*, *5*, 152–159.

Bowie, C., & Harvey, P. (2006). Administration and interpretation of the Trail Making Test. *Nature Protocols*, *1*(5), 2277–2281. https://doi.org/10.1038/nprot.2006.390

Bruchhage, M. M. K., Ngo, G. C., Schneider, N., D'Sa, V., & Deoni, S. C. L. (2020). Functional connectivity correlates of infant and early childhood cognitive development. *Brain Structure & Function*, *225*(2), 669–681. https://doi.org/10.1007/s00429-020-02027-4

Butterfield, S. A., Angell, R. M., & Mason, C. A. (2012). Age and sex differences in object control skills by children ages 5 to 14. *Perceptual and Motor Skills*, *114*(1), 261–274. https://doi.org/10.2466/10.11.25.PMS.114.1.261-274

Cameron, C. E., Cottone, E. A., Murrah, W. M., & Grissmer, D. W. (2016). How are motor skills linked to children's school performance and academic achievement? *Child Development Perspectives*, *10*(2), 93–98. https://doi.org/10.1111/cdep.12168

Clouston, S. A., Brewster, P., Kuh, D., Richards, M., Cooper, R., Hardy, R., Rubin, M. S., & Hofer, S. M. (2013). The dynamic relationship between physical function and cognition in longitudinal aging cohorts. *Epidemiologic Reviews*, *35*(1), 33–50. https://doi.org/10.1093/epirev/mxs004

Cohen, J. (1988). *Statistical Power Analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates, Publishers.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*(1), 155–159. https://doi.org/10.1037/0033-2909.112.1.155

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child development*, *71*(1), 44–56. https://doi.org/10.1111/1467-8624.00117

Douw, L., Nieboer, D., van Dijk, B. W., Stam, C. J., & Twisk, J. W. (2014). A healthy brain in a healthy body: Brain network correlates of physical and mental fitness. *PLoS ONE*, *9*(2), e88202. https://doi.org/10.1371/journal.pone.0088202

Fulceri, F., Grossi, E., Contaldo, A., Narzisi, A., Apicella, F., Parrini, I., Tancredi, R., Calderoni, S., & Muratori, F. (2019). Motor skills as moderators of core symptoms in autism spectrum disorders: Preliminary data from an exploratory analysis with artificial neural networks. *Frontiers in Psychology*, *9*, 2683. https://doi.org/10.3389/fpsyg.2018.02683

Gaillard, A., Fehring, D. J., & Rossell, S. L. (2020). A systematic review and meta-analysis of behavioural sex differences in executive control. *European Journal of Neuroscience*, *53*(2), 519–542. https://doi.org/10.1111/ejn.14946

Gandotra, A., Kótyuk, S., Sattar, Y., Bizonics, V., Csaba, R., Cserényi, R., & Cserjesi, E. (2021). A meta-analysis of the relationship between motor skills and executive functions in typically-developing children. *Journal of Cognition and Development*, *23*(1), 83–110. https://doi.org/10.1080/15248372.2021.1979554

Gómez-Pinilla, F., & Hillman, C. (2013). The influence of exercise on cognitive abilities. *Comprehensive Physiology*, *3*(1), 403–428. https://doi.org/10.1002/cphy.c110063

Grissom, N. M., & Reyes, T. M. (2019). Let's call the whole thing off: Evaluating gender and sex differences in executive function. *Neuropsychopharmacology*, *44*(1), 86–96. https://doi.org/10.1038/s41386-018-0179-5

Hemmelmann, C., Brose, S., Vens, M., Hebebrand, J., & Ziegler, A. (2010). Perzentilen des body-mass-index auch für 18- bis 80-Jährige? Daten der Nationalen Verzehrsstudie II. *Deutsche medizinische*

Wochenschrift, 135(17), 848–852. https://doi.org/10.1055/s-0030-1253666
Holfelder, B., Klotzbier, T. J., Eisele, M., & Schott, N. (2020). Hot and cool executive function in elite- and amateur- adolescent athletes from open and closed skills sports. *Frontiers in Psychology*, *11*, Article 694. https://doi.org/10.3389/fpsyg.2020.00694
Holfelder, B., & Schott, N. (2014). Relationship of fundamental movement skills and physical activity in children and adolescents: A systematic review. *Psychology of Sport and Exercise*, *15*(4), 382–391. https://doi.org/10.1016/j.psychsport.2014.03.005
Holfelder, B., & Schott, N. (2021). Object control skill performance across the lifespan: A cross-sectional study. *Research Quarterly for Exercise & Sport*, *93*(4), 825–834. Online ahead of print. https://doi.org/10.1080/02701367.2021.1924351
Holfelder, B., Stierle, P., Hohmann, T., & Schott, N. (2013). *Der Schuss im Fussball: Eine qualitative und quantitative Analyse*. Sportmotorik-Tagung der Deutschen Vereinigung fuer Sportwissenschaft.
Huijgen, B. C. H., Leemhuis, S., Kok, N. M., Verburgh, L., Oosterlaan, J., Elferink- Gemser, M. T., & Visscher, C. (2015). Cognitive functions in elite and sub-elite youth soccer players aged 13 to 17 years. *PLoS ONE*, *10*, e0144580. https://doi.org/10.1371/journal.pone.0144580
Jauny, G., Eustache, F., & Hinault, T. (2022). Connectivity dynamics and cognitive variability during aging. *Neurobiology of Aging*, *118*, 99–105. https://doi.org/10.1016/j.neurobiolaging.2022.07.001
Jeannerod, M. (2006). *Motor cognition: What actions tell the self*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198569657.001.0001
Kaiser, M. L., Schoemaker, M. M., Albaret, J. M., & Geuze, R. H. (2015). What is the evidence of impaired motor skills and motor control among children with attention deficit hyperactivity disorder (ADHD)? Systematic review of the literature. *Research in Developmental Disabilities*, *36C*, 338–357. https://doi.org/10.1016/j.ridd.2014.09.023
Karimpoor, M., Churchill, N. W., Tam, F., Fischer, C. E., Schweizer, T. A., & Graham, S. J. (2017). Tablet-Based Functional MRI of the trail making test: Effect of Tablet interaction mode. *Frontiers in Human Neuroscience*, *11*, 496. https://doi.org/10.3389/fnhum.2017.00496
Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012
Kromeyer-Hauschild, K., Wabitsch, M., Kunze, D., Geller, F., Geiß, H. C., Hesse, V., von Hippel, A., Jaeger, U., Johnsen, D., Korte, W., Menner, K., Müller, G., Müller, J. M., Niemann-Pilatus, A., Remer, T., Schaefer, F., Wittchen, H.-U., Zabransky, S., & Hebebrand, J. (2001). Perzentile für den Body-mass-Index für das Kindes- und Jugendalter unter Heranziehung verschiedener deutscher Stichproben. *Monatsschrift Kinderheilkunde*, *149*(8), 807–818. https://doi.org/10.1007/s001120170107
Leisman, G., Braun-Benjamin, O., & Melillo, R. (2014). Cognitive-motor interactions of the basal ganglia in development. *Frontiers in Systems Neuroscience*, *8*, 16. https://doi.org/10.3389/fnsys.2014.00016
Leisman, G., Moustafa, A. A., & Shafir, T. (2016). Thinking, walking, walking: Integratory motor and cognitive brain function. *Frontiers in Public Health*, *4*, 94. https://doi.org/10.3389/fpubh.2016.00094
Linari, I., Juantorena, G. E., Ibánez, A., Petroni, A., & Kamienkowski, J. E. (2022). Unveiling Trail Making Test: Visual and manual trajectories indexing multiple executive processes. *Scientific Reports*, *12*(1), 14265. https://doi.org/10.1038/s41598-022-16431-9
Logan, S. W., Barnett, L. M., Goodway, J. D., & Stodden, D. F. (2017). Comparison of performance on process- and product-oriented assessments of fundamental motor skills across childhood. *Journal of Sports Sciences*, *35*(7), 634–641. https://doi.org/10.1080/02640414.2016.1183803
López-Moliner, J., Brenner, E., Louw, S., & Smeets, J. B. J. (2010). Catching a gently thrown ball. *Experimental Brain Research*, *206*(4), 409–417. https://doi.org/10.1007/s00221-010-2421-1
Lorson, K. M., Stodden, D. F., Langendorfer, S. J., & Goodway, J. D. (2013). Age and gender differences in adolescent and adult overarm throwing. *Research Quarterly for Exercise & Sport*, *84*(2), 239–244. https://doi.org/10.1080/02701367.2013.784841
Ludyga, S., Pühse, U., Gerber, M., & Herrmann, C. (2018). Core executive functions are selectively related to different facets of motor competence in preadolescent children. *European Journal of Sport Science*, *19*(3), 375–383. https://doi.org/10.1080/17461391.2018.1529826
Mally, K. K., Battista, R. A., & Roberton, M. A. (2011). Distance as a control parameter for place kicking. *Journal of Human Sport & Exercise*, *6*(1), 122–134. https://doi.org/10.4100/jhse.2011.61.14
Marrus, N., Eggebrecht, A. T., Todorov, A., Elison, J. T., Wolff, J. J., Cole, L., Gao, W., Pandey, J., Shen, M. D., Swanson, M. R., Emerson, R. W., Klohr, C. L., Adams, C. M., Estes, A. M., Zwaigenbaum, L., Botteron, K. N., McKinstry, R. C., Constantino, J. N., & Pruett, J. R. (2018). Walking, gross motor development, and brain functional connectivity in infants and toddlers. *Cerebral Cortex*, *28*(2), 750–763. https://doi.org/10.1093/cercor/bhx313
McClelland, M. M., & Cameron, C. E. (2019). Developing together: The role of executive function and motor skills in children's early academic lives. *Early Childhood Research Quarterly*, *46*, 142–151. https://doi.org/10.1016/j.ecresq.2018.03.014
Montagne, G., Laurent, M., Durey, A., & Bootsma, R. (1999). Movement reversals in ball catching. *Experimental Brain Research*, *129*(1), 87–92. https://doi.org/10.1007/s002210050939
Morgan, P. J., Barnett, L. M., Cliff, D. P., Okely, A. D., Scott, H. A., Cohen, K. E. & Lubans, D. R. (2013). Fundamental movement skill interventions in youth: A systematic review and meta-analysis. *Pediatrics*, *132*(5), e1361–1383. https://doi.org/10.1542/peds.2013-1167
Nóbrega-Sousa, P., Gobbi, L. T. B., Orcioli-Silva, D., Conceição, N. R. D., Beretta, V. S., & Vitório, R. (2020). Prefrontal cortex activity during walking: Effects of aging and associations with gait and executive function. *Neurorehabilitation and Neural Repair*, *34*(10), 915–924. https://doi.org/10.1177/1545968320953824
Northey, J. M., Cherbuin, N., Pumpa, K. L., Smee, D. J., & Rattray, B. (2018). Exercise interventions for cognitive function in adults older than 50: A systematic review with meta-analysis. *British Journal of Sports Medicine*, *52*(3), 154–160. https://doi.org/10.1136/bjsports-2016-096587
Peel, N. M., Alapatt, L. J., Jones, L. V., & Hubbard, R. E. (2019). The association between gait speed and cognitive status in community-dwelling older people: A systematic review and meta-analysis. *The Journals of Gerontology Series A Biological Sciences and Medical Sciences*, *74*(6), 943–948. https://doi.org/10.1093/gerona/gly140
Poldrack, R. A., Sabb, F. W., Foerde, K., Tom, S. M., Asarnow, R. F., Bookheimer, S. Y., & Knowlton, B. J. (2005). The neural correlates of motor skill automaticity. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *25*(22), 5356–5364. https://doi.org/10.1523/JNEUROSCI.3880-04.2005
Raab, M., & Green, N. (2005). Motion as input: A functional explanation of movement effects on cognitive processes. *Perceptual and Motor Skills*, *100*(2), 333–348. https://doi.org/10.2466/pms.100.2.333-348
Reitan, R. M. (1958). The relationship of the trail making test to organic brain damage. *Journal of Consulting & Clinical Psychology*, *19*, 393–394. https://doi.org/10.1037/h0044509
Rigdon, B., & Loprinzi, P. D. (2019). The association of cardiorespiratory fitness on memory function: Systematic review. *Medicina (Kaunas, Lithuania)*, *55*(5), 127. https://doi.org/10.3390/medicina55050127
Roberton, M. A., & Halverson, L. E. (1984). *Developing children - their changing movement: A guide for teachers*. Lea & Febiger.
Rosenbaum, D. A., Carlson, R. A., & Gilmore, R. O. (2001). Acquisition of intellectual and perceptual-motor skills. *Annual Review of Psychology*, *52*, 453–470. https://doi.org/10.1146/annurev.psych.52.1.453
Salthouse, T. A. (2011). What cognitive abilities are involved in trail-making performance? *Intelligence*, *39*(4), 222–232. https://doi.org/10.1016/j.intell.2011.03.001
Schoenfeld, B. J. (2013). Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. *Sports Medicine*, *43*(3), 179–194. https://doi.org/10.1007/s40279-013-0017-1
Schott, N., El-Rajab, I., & Klotzbier, T. (2016). Cognitive-motor interference during fine and gross motor tasks in children with developmental

coordination disorder. *Research in Developmental Disabilities*, *57*, 136–148. https://doi.org/10.1016/j.ridd.2016.07.003

Schott, N., & Holfelder, B. (2015). Relationship between motor skill competency and executive function in children with Down's syndrome. *Journal of Intellectual Disability Research*, *59*(9), 860–872. https://doi.org/10.1111/jir.12189

Schott, N., & Klotzbier, T. (2018). The motor-cognitive connection: Indicator of future developmental success in children and adolescents?! In R. P. Bailey, R. Meeusen, S. Schäfer-Cerasari, & P. Tomporowski (Eds.), *Physical activity and educational achievement: Insights from exercise neuroscience* (pp. 111–129). Routledge. https://doi.org/10.4324/9781315305790-7

Smith, E., Cusack, T., Cunningham, C., & Blake, C. (2017). The influence of a cognitive dual task on the gait parameters of healthy older adults: A systematic review and meta-analysis. *Journal of Aging and Physical Activity*, *25*(4), 671–686. https://doi.org/10.1123/japa.2016-0265

St Laurent, C. W., Burkart, S., Andre, C., & Spencer, R. M. C. (2021). Physical activity, fitness, school readiness, and cognition in early childhood: A systematic review. *Journal of Physical Activity and Health*, *18*(8), 1004–1013. https://doi.org/10.1123/jpah.2020-0844

Strohmeyer, H. S., Williams, K., & Schaub-George, D. (1991). Developmental sequences for catching a small ball: A prelongitudinal screening. *Research Quarterly for Exercise & Sport*, *62*(3), 257–266. https://doi.org/10.1080/02701367.1991.10608722

van der Fels, I. M. J., Smith, J., de Bruijn, A. G. M., Bosker, R. J., Königs, M., Oosterlaan, J., Visscher, C., & Hartman, E. (2019). Relations between gross motor skills and executive functions, controlling for the role of information processing and lapses of attention in 8-10 year old children. *PLoS ONE*, *14*(10), e0224219. https://doi.org/10.1371/journal.pone.0224219

van der Fels, I. M. J., Wierikea, 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. https://doi.org/10.1016/j.jsams.2014.09.007

Verburgh, L., Scherder, E. J., Van Lange, P. A., & Oosterlaan, J. (2014). Executive functioning in highly talented soccer players. *PLoS ONE*, *9*, e91254. https://doi.org/10.1371/journal.pone.0091254

Weisberg, A., Le Gall, J., Stergiou, P., & Katz, L. (2020). Comparison of two methods to estimate the maximal velocity of a ball during an overhand throw. *Proceedings*, *49*(43), 1–6. https://doi.org/10.3390/proceedings2020049043

Wood, J. M., Black, A. A., Hopkins, S., & White, S. L. J. (2018). Vision and academic performance in primary school children. *Ophthalmic & Physiological Optics*, *38*(5), 516–524. https://doi.org/10.1111/opo.12582

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders: Official Journal of the Movement Disorder Society*, *23*(3), 329–472. https://doi.org/10.1002/mds.21720

Zheng, Y., Ye, W., Korivi, M., Liu, Y., & Hong, F. (2022). Gender differences in fundamental motor skills proficiency in children aged 3-6 years: A systematic review and meta-analysis. *International Journal of Environmental Research and Public Health*, *19*(14), 8318. https://doi.org/10.3390/ijerph19148318