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Aiming-Catching Skills, Manual Dexterity and Spatial Reasoning in Preschool Children: A Moderated Meditation Model

Zdolności do celowania-łapania, zdolności manipulacyjne oraz rozumowanie przestrzenne u dzieci w wieku przedszkolnym: model moderowanej mediacji

Abstract. In the early years of life, motor skills contribute to the formation of cognitive skills. The aim of the present study (conducted in June 2021) was to determine mutual relationships between motor variables: aiming-catching as well as manual dexterity, and the cognitive variable of spatial reasoning. It was assumed that manual dexterity played a mediating role in the relationship between agility skills and spatial reasoning. A second aim of study was to test the assumption that age played a moderating role in the relationship between manual dexterity and spatial reasoning. The participants were Polish preschool children ($N = 83$), including 42 boys (100% white race of children from Eastern Poland). The results indicated that manual dexterity mediated the relationship between aiming-catching skills and spatial reasoning. Age was an important moderator of the relationship between manual dexterity and spatial reasoning.

Keywords: cognitive development, motor skills, spatial reasoning, manual dexterity, aiming and catching skills

Słowa kluczowe: rozwój poznawczy, rozumowanie przestrzenne, sprawność motoryczna, zdolności manipulacyjne, zdolności celowania-łapania

INTRODUCTION

The role of physical activity in children's development is particularly appreciated by educators, sensory integration therapists, and physiotherapists (Dimitri et al., 2020; Harsha, Berenson, 1995; Janssen, LeBlanc, 2010). The importance of movement for health and broadly understood well-being has been the focus of numerous analyses (also those conducted in the context of the pandemic), which emphasize the positive impact that physical activity has on children (Papaioannou et al., 2020; Rhodes et al., 2017). Despite this theoretical awareness, most parents, as research shows, do not provide enough physical activity to their offspring (Kolipińska, Nałęcz, 2018; Nałęcz, Mazur, Fijałkowska, 2021). This is a serious problem since parents' beliefs and behaviors related to physical activity affect how much physical activity the child is getting (Delaney et al., 2019; Petersen et al., 2020). Many researchers take part in the socially important debate aimed at promoting physical activity in children by showing how broad an impact it has on a young person's development. The growing awareness of the importance of movement in children's lives has encouraged numerous scholars to delve into these issues, also with regard to the mutual relationships between motor and cognitive development (Martzog et al., 2019; Sember et al., 2020; Veldman et al., 2018). Studies in this area, apart from providing arguments for promoting children's physical activity, also allow to set new therapeutic trends. The fact that cognitive skills stimulate motor activity and vice versa can be exploited by specialists working with both healthy children and those with deficits.

When addressing an issue that is so vital and topical, it is extremely important to look for conclusions that have broad ramifications and allow to advance a certain ordered vision of the investigated relationships. Unfortunately, the data published so far are beset with inaccuracies and also lack a more general context. Research on relationships between human motor and intellectual development points to the existence of certain associations between specific motor functions and specific cognitive functions (Davis et al., 2011), rather than looking for connections at the level of general factors. Various authors suggest that fine motor skills and balance are related to memory, attention, reasoning, and executive and other functions (El-Hady et al., 2018; Martzog et al., 2019; Oberer et al., 2018). However, their findings do not clearly show which functions are the most strongly connected, and also there are no studies examining associations between gross motor skills and fine motor skills in relation to cognitive skills.

Unfortunately, most of the investigations conducted so far provide contradictory information on the relationships between motor and cognitive development. Đorđić, Tubić and Jakšić (2016) did not find any associations between gross motor skills and intelligence, while other authors demonstrated that these variables are related to one another (Yu et al., 2016; Yu et al., 2018). Similarly, findings concerning the age at which these relationships are most perspicuous are inconsistent; while some researchers point to the period of early and middle childhood (Kuzik et al., 2020; Reilly et al., 2008), others claim that the relationships have a similar strength throughout childhood to adolescence (Fels et al., 2015; Ishihara et al., 2018). It is worth emphasizing that these issues have been considered with regard to children of various age groups, which is why the results are very difficult to compare.

In their effort to establish the role of the child's age in the relationship between motor and cognitive functions, researchers mostly use research design based on comparing age groups and measuring the strength of the relationship. There are no studies which would explain the mechanisms involved and possible interactions among the various factors during child development. Despite clues from neurobiology regarding the similarity of the activity of structures responsible for motor and cognitive functioning (Diamond, 2007), as well as the importance of critical periods in the development of various brain regions (Graf et al., 2021; Shonkoff et al., 2009), there is no research into the role of the child's age in the relationship between physical and intellectual abilities.

The goal of this paper was to make a step towards unifying data from across different studies by verifying the model based on the conditioned mediation process. The structure of the model refers to the work of other researchers who have suggested that there are relationships between specific motor and cognitive functions (Davis et al., 2011). The model also exploits the concept of proximodistal motor development in children, which describes the sequence in which motor skills develop from large and uncoordinated to small and precise movements

(McBryde, Ziviani, 1990). We tried to take into account the numerous studies and conclusions that are discussed later on in this article. They led us to the assumption that there existed an age-dependent relationship among gross motor skills (aiming-catching skills), fine motor skills (manual dexterity), and the cognitive variable of spatial reasoning.

Relationships between motor and cognitive development

The motor development of preschool children is very dynamic. In the preschool period, children acquire new gross and fine motor skills, such as catching and throwing, movement combinations, such as run-jump-run, as well as cycling, roller skating, climbing a tree, buttoning, and graphomotor skills. It is in this period that the child has a great need to move, which is often referred to as "hunger for movement". As they engage in motor activities and have various polysensory experiences, including kinesthetic ones, children gather information about the world and about themselves. They learn new textures and colors, get to know new places and people, and observe the phenomena occurring in their surroundings. These activities lead to the development of perception, thinking, attention, memory, and spatial orientation. Moreover, in preschool children, physical activity itself requires the activation of cognitive processes. For example, keeping the body in a sitting position engages attention. With age, motor activities become more and more automatic and less of a burden on cognitive functions. The older the child is, the more motor and cognitive development become independent of one another. This means that age plays an important role in shaping the associations between motor and cognitive functions (Kielar-Turska, 2011a; Shaffer, Kipp, 2009).

Manual dexterity are deliberate, precise movements of the arms, wrists and fingers. Fine hand movements are the dominant type of movement here. Larger arms movements play a secondary role, but they are indispensable for performing small motions. Manual dexterity belong to the group of fundamental skills, i.e. skills that most people have. They are acquired in the course of life to allow individuals to perform basic motor and self-help activities. They are shaped in the process of learning and development (Raczek, 2010)). In this paper, the term "manual dexterity" is refer to the small motor movements of the hands, fingers and wrists and so that it is used interchangebly with the term "fine motor skills". *Aiming-catching skills* are commonly defined as coordination skills involved in subtle motions of body parts such as the arms and hands (Denisiuk et al., 1967; Fugiel, 2017; Meinel, 1967; Nowicki, 1988). *Reasoning* is "drawing conclusions from premises" (Nęcka et al., 2006). *Spatial reasoning* is visual thinking, which involves processing of information represented in the imagery system (Fecenec et al., 2015). Below, we present an overview of research on the relationships among manual dexterity, aiming-catching skills, and reasoning.

Jaščenoka and colleagues (2018) studied the relationship between motor and cognitive performance in children aged 3–6 years. They showed that the Visual Spatial score differed among children with low, medium, and high Motor Performance scores. Better Motor Performance correlated with better Visual Spatial scores. Martzog and colleagues (2012) investigated associations between manual skills and reasoning in preschool children. They showed that dexterity was related to reasoning. This relationship existed even when the variable interfering with this relationship – attention – was controlled for. It turned out that hand-eye coordination was also related to reasoning, however, this relationship lost its significance when the variable of attention was taken into account. On the other hand, fine-motor-speed was unrelated to cognitive abilities. Macdonald and colleagues (2018) demonstrated that fine motor proficiency was positively associated with academic performance in mathematics and reading, especially in the first years of school education. Research also indicates that fine motor skills indirectly affect mathematics skills via eye-hand coordination (Kim et al., 2018). Martzog and colleagues (2019) studied three types of fine motor skills: dexterity, graphomotor skills, and speed-dominated fine motor skills, and their associations with nonverbal reasoning in preschool children. They observed a link between dexterity and reasoning after controlling for age, attention, and processing speed. They also found a cross-lagged link from four-year-old children's dexterity to their reasoning skills at the age of five. This and other studies (Higashiona et al., 2017) indicate that there exist relationships between manual skills and cognitive abilities, including reasoning.

Westendorp and colleagues (2014), who examined ball skills (aiming-catching skills) in children with learning difficulties, showed that those skills were related to executive functions (problem-solving). Other studies indicated that aiming-catching skills acted as a mediator between physical training and executive functions (inhibition) (Pesce et al., 2016). On the other hand, a study by Iannuzzi and colleagues (2016) showed that aiming-catching skills were not related to language skills in children with type 1 neurofibromatosis.

Age-moderated mediation between child aiming-catching skills and spatial reasoning via manual dexterity

The studies cited in the previous section provide evidence that there is a relationship between a child's motor and cognitive performance. Because they have been conducted in different age groups, it is possible that this relationship is universal, but this is a speculation that requires further verification. Unfortunately, there are no interactive models that would highlight the role of the child's age in shaping these relationships. Similarly, the issue of more specific mechanisms responsible for the link between motor and cognitive abilities has not yet been addressed.

For these reasons, we wanted to verify the model of conditional mediation between aiming-catching skills and spatial reasoning via manual dexterity, in which the child's age plays the role of a moderator. One can assume, on the basis of the laws of child developmental psychology, that there exists a relationship between manual and aiming-catching skills. Proximodistal development is the development of motor functions that starts at the center of an organism and then radiates outwards toward the extremities. This means that in order to properly develop fine hand movements, the child first has to develop gross arm movements (Harwas-Napierała, Trempała, 2004). This law allows one to assume that the acquisition of aiming-catching skills is a precondition for the development of manual dexterity. Although this pattern of motor development was questioned already in the last century (Loria, 1980), scientists emphasize the sequential nature of these processes despite their probable neurobiological distinctiveness (McBryde, Ziviani, 1990; Vesa et al., 2017).

Age plays the part of a key moderator in most developmental processes (Kielar-Turska, 2007). However, as previous research shows, its role in the context of the relationship between motor and cognitive development is unclear (Davis et al., 2011; Fels et al., 2015; Ishihara et al., 2018; Kuzik et al., 2020; Reilly et al., 2008). It seems logical then to try to explain the contradictory conclusions from research by including the variable of age in the model not as a factor describing the groups compared, but as a moderator of the investigated relationships.

Because the results of the studies carried out so far are highly inconsistent, it is difficult to conclude what cognitive variable is the most strongly related to motor performance. However, there are theoretical and empirical arguments which show that motor skills play a large role in the development of spatial reasoning (Jaščenoka et al., 2018; Newcombe, Frick, 2010). It seems that a higher level of motor activity, and in particular manual dexterity, allows an individual to better reproduce, in the mental space, the processes related to rotating figures or imagining a specific space.

In this light, we will try to test two main hypotheses. Firstly, we assume that there is a mediation process in which aiming-catching skills are related to spatial reasoning via manual dexterity. And secondly, we assume that this process is determined by the child's age and is more pronounced in younger children. The model discussed is shown graphically in Figure 1.

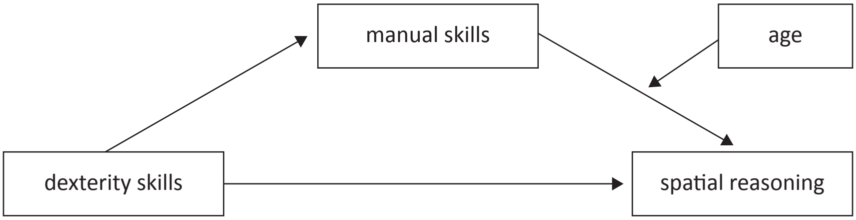

Figure 1. Model of relationships among the variables of aiming-catching skills, manual dexterity, spatial reasoning, and age

METHOD

Participants

The sample consisted of 86 polish (Podkarpackie and Lubelskie Voivodeships) preschool children aged 3–5. The socioeconomic status of the children's origin was good. The study sample included 100% of White children. Forty one (41) girls and forty five (45) boys were surveyed. When the results of the survey were analyzed, it turned out that five of the children obtained scores that were significantly different from those of the remaining participants. This was probably due to the occurrence of a disruptive situation during the administration of the survey or the children having clearly distinct levels of the characteristics measured. For this reason, their scores were excluded from further analyses, so the final sample size was 83 children aged 3–5 (M = 4.89; SD = 0.68, 51.8% boys). The children's health status was taken into account when recruiting the sample. Only those children who showed no symptoms of developmental disorders were included.

Procedure

Prior to the study, consent was obtained from the Ethical Scientific Research Committee of the xxx at the xxx (xxx). Written consents to participate in the study were also obtained from the parents of the study children. The survey was conducted in a preschool physical activity room in June 2021. All participants took the tasks individually. Each child was surveyed using the following measures, in this order: Intelligence and Development Scale for Preschool Children (IDS-P) – the cognitive domain, and the Movement Assessment Battery for Children (M-ABC2).

Measures

Intelligence and Development Scale for Preschool Children (IDS-P). The IDS-P scale by Fecenec, Jaworowska and Matczak (2015) is used to assess the level of development of a child's various skills and abilities. For the purposes of this study, scales for measuring cognitive abilities, including spatial reasoning, were used. The children's task was to replicate a pattern originally arranged from blocks by the experimenter. The reliability of the IDS-P was assessed using internal consistency and stability. The Spearman-Brown internal consistency coefficient for *Spatial Reasoning* was r = .90. The stability of the individual scales was measured using the test-retest method. The test-retest correlation coefficient for *Spatial Reasoning* was r = .83 (Fecenec, Jaworowska, and Matczak, 2015).

Movement Assessment Battery for Children. The M-ABC2 is a British assessment tool used for measuring motor activity in children and adolescents aged 3–16 years. The battery, developed by Henderson, Sugden and Barnett (2007), is used to assess the level of motor performance and to identify a delay or impairment in motor development. It consists of eight tasks for each of three age bands: 3–6 years, 7–10 years, and 11–16 years. The M-ABC2 measures the following types of motor abilities: manual dexterity, aiming-catching skills and balance. The manual dexterity tests involve posting coins, threading beads, and tracing. Aiming-catching skills are measured using beanbag aiming and catching tests. The reliability of the tool was verified by test-retest and estimation of the stability coefficient. Pearson's correlation coefficients r for the individual scales were as follows: *Manual Dexterity:* $r = .77$; *Aiming and Catching:* $r = .84$. For the purposes of this present study, test instructions had been translated into Polish (Henderson, Sugden, Barnett, 2007).

Data analysis

The data were analyzed in two steps using IBM SPSS Statistics v27. In the first step, the results were described statistically taking into account Pearson's correlation coefficient r. Also, the mean values of the variables measured were compared between genders. In the second step, the mediation and moderated mediation models were verified using the PROCESS macro for SPSS (Hayes, 2018). Standardized regression coefficients were used for both direct and indirect effects of the independent variable on the dependent variable, taking the mediator into consideration. Effect sizes were calculated by bootstrapping (5000 samples) at a 95% confidence interval.

RESULTS

Statistical description of the results and correlation coefficients

In the first step of the statistical analysis, correlations were calculated between aiming-catching skills, manual dexterity and spatial reasoning. They are shown in Table 1.

Table 1. Descriptive statistics and correlation coefficients for aiming-catching skills, manual skills and spatial reasoning

Variables	*M*	*SD*	*1.*	*2.*	*3.*
1. Aiming-catching skills	20.77	4.46	–	–	–
2. Manual skills	28.64	5.76	.26*	–	–
3. Spatial reasoning	7.43	2.85	.24*	.32**	–

Note: $^*p < .05$; $^{**}p < .01$

As can be seen, all the correlations between the variables were significant and positive. It can therefore be said that a high level of aiming-catching skills and manual dexterity was associated with a high level of cognitive performance, represented here by spatial reasoning. It is also worth emphasizing that boys differed from girls in their spatial reasoning scores – boys had a significantly higher level of this ability ($t_{(81)} = -4.02$, $p < .001$).

Mediation analysis

As a next step in the analysis, we tested the mediation model (Model 4) using the bootstrapping procedure recommended by Hayes (2018). The goal was to determine whether manual dexterity mediated the relationship between aiming-catching skills and spatial reasoning. In order to assess the direct and indirect effects, the following conditions were set: number of bootstrap samples = 5000; 95% bias-corrected confidence intervals. The results are shown in Table 2.

Table 2. Results of mediation analysis for manual dexterity as a mediator in the relationship between aiming-catching skills and spatial reasoning

Variables	*B*	*SE*	*t (LLCI, ULCI)*	*R2 of the model*
Direct effects				
Aiming-catching skills – Manual dexterity	.34	.14	2.36 (.05, .61)	.07*
Manual dexterity – Spatial reasoning	.14	.05	2.56 (.03, .24)	
Aiming-catching skills – Spatial reasoning	.11	.07	1.51 (−.03, .25)	.13**
Indirect effects	*Effect*	*SE*	*LLCI*	*ULCI*
Aiming-catching skills – Manual dexterity – Spatial reasoning	.05	.03	.01	.10

Note: $^*p < .05$; $^{**}p < .01$

The direct effects evaluated in the model indicated that aiming-catching skills were positively correlated with manual dexterity; however, when the mediator was included in the model, the relationship between aiming-catching skills and spatial reasoning became statistically non-significant. Manual dexterity, on the other hand, were positively associated with spatial reasoning. The indirect effect showed that manual dexterity were an important mediator between aiming-catching skills and spatial reasoning. Since the direct effect of manual dexterity on spatial reasoning was non-significant, one can speak of a full mediation in this case. Aiming-catching skills are associated with better manual dexterity, which translates into the child's better spatial reasoning. The model we obtained explained 13% of the variance, which is not a high result, and so, in accordance with the research plan, we next included age as a moderator in the model.

Moderated mediation analysis

In order to determine whether a child's age was a moderator of the indirect effects between aiming-catching skills and spatial reasoning via manual dexterity, a moderated mediation analysis was performed (Model 14). Bootstrapping procedures similar to those carried out in the previous analysis were used (number of bootstrap samples = 5000; 95% bias-corrected confidence intervals). The results are shown in Table 3.

Table 3. Moderated mediation analysis with age as a moderator

Variables	*B*	*SE*	*t (LLCI, ULCI)*	*R2 of the model*
Direct effects				
Aiming-catching skills – Manual dexterity	.34	.14	2.36 (.05, .61)	.07*
Manual dexterity – Spatial reasoning	.85	.30	2.84 (.25, 1.44)	
Aiming-catching skills – Spatial reasoning	.07	.06	1.32 (−.04, .19)	

Age – Spatial reasoning	6.36	1.75	3.64 (2.88, 9.83)	
Interaction Manual dexterity × Age	−.14	.06	−2.35(−.26,−.02)	.46***
Conditional indirect effect	*Effect*	*SE*	*LLCI*	*ULCI*
Age: 4.1 years	.09	.04	.02	.19
Age: 5.1 years	.04	.02	.01	.09
Age: 5.6 years	.02	.02	−.03	.06
Moderated mediation index				
Manual dexterity as mediator and Age as moderator	−.05	.03	−.12	−.01

Note: **p* < .05; ****p* < .001

There were statistically significant direct effects between aiming-catching skills and manual dexterity, manual dexterity and spatial reasoning, and age and spatial reasoning. The interaction between manual dexterity and age was also significant, as was the moderated mediation index, which indicates that age was a significant moderator of the indirect effect between aiming-catching skills and spatial reasoning via manual dexterity (indirect effect = −.05, CI_{95} = − .12, .01). A comparison between the mediation model and the moderated mediation model showed that there was a 33% difference in the variance explained, $\Delta R^2 = .33$ The conditional indirect effect was higher in younger children, which means that the assumptions made prior to the study were correct, as shown in Figure 2.

DISCUSSION

The aim of this study was to determine the relationship of the motor variables of aiming-catching skills and manual dexterity with the cognitive variable of spatial reasoning, with the participants' age as a moderating variable. We assumed that there existed a mediation relationship between aiming-catching skills and spatial reasoning, with manual dexterity playing the role of the mediator. We also hypothesized that age was the moderator in the relationship between manual dexterity and spatial reasoning. Our findings confirmed these hypotheses.

A high manual dexterity score was associated with a high spatial reasoning score, which was in line with the results obtained earlier by other researchers (Jaščenoka et al., 2018).

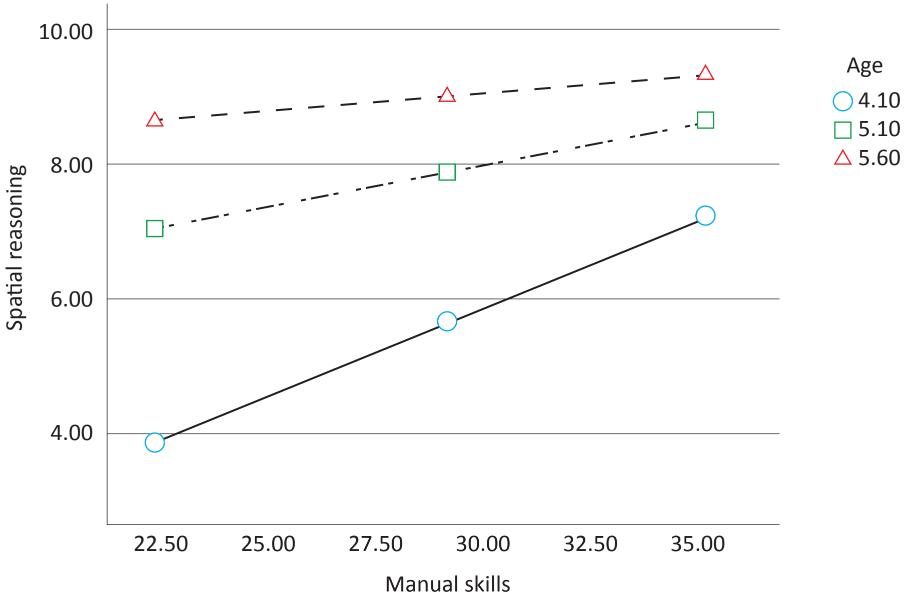

Figure 2. The moderating effect of age on the effect of manual dexterity on spatial reasoning

Aiming-catching skills were also positively correlated with spatial reasoning. Previous studies had not tested this relationship. Moreover, they provided contradictory findings regarding the relationship of aiming-catching skills with other cognitive variables (Iannuzzi et al., 2016; Westendorp et al., 2014). Further analyses showed that when the mediator (manual dexterity) was included in the model, the relationship between aiming-catching skills and spatial reasoning became non-significant, and the relationship between manual dexterity and spatial reasoning was positive. These results confirm the hypothesis about the mediating role of manual dexterity in the relationship between aiming-catching skills and spatial reasoning. It is worth emphasizing, however, that the basic variant of the model (without age as the moderator) explained only 13% of the variance in the dependent variable. It can therefore be said, regarding the group of children aged 3 to 5 as a whole, that the proposed model shows a low but statistically significant accuracy.

When trying to explain the results, it is worth raising two issues. The first one relates to the laws of developmental psychology. In accordance with the concept of proximodistal development, a child must first master large arms movements (aiming-catching skills) before s/he can learn small movements (manual dexterity) (Harwas-Napierała, Trempała, 2004). This means that the development of manual dexterity precedes and determines the development of cognitive abilities (spatial reasoning) (Kielar-Turska, 2011a). The second explanation makes reference to the neurobiological background and points to the similarity of the nervous system structures responsible for motor activity and specific cognitive functions (Diamond, 2000; 2007). Given this similarity, it can be supposed that the brain regions responsible for precise hand movements contribute in some way to the development of imagery skills associated with very similar activities – rotating figures or analyzing space.

An element that significantly increased the proportion of explained variance in these relationships was the moderating function of the child's age. Our results suggest that the relationship between a child's manual dexterity and spatial reasoning depends to a large extent on his or her age. In younger children (around 4 years old), this association is clearly stronger than in children over 5 years old. The observed interaction of age with the other factors is strong, as shown by the difference in the variance explained (13% *vs* 46%). Thus, it can be said that with age, the effect of motor skills on cognitive abilities weakens, as predicted by the developmental laws regarding preschool children. Initially interdependent functions and activities become more and more independent of one another, a phenomenon that is referred to as "differentiation" in developmental psychology (Kielar-Turska, 2011a). Trempała (2012, p. 19) says that "development is understood as a change in the long-term process of directed differentiation of activities, functions or mental processes." This observation corresponds, in a way, with the results of research conducted so far. Various authors have assumed that the relationship between motor and cognitive abilities is non-linear and age-dependent (Dyck et al., 2009), and that the associations between individual motor and intellectual functions are stronger in younger children (Reilly et al., 2008). At the same time, the present paper elaborates on the topic of the autonomy of the individual aspects of development in older children, which has already been touched upon in some studies (Jenni et al., 2013).

It can be said that our (successfully verified) model of moderated mediation opens up a new perspective on relationships between motor and cognitive functions. It clearly emphasizes that these associations are age-dependent, which is in concert with the already mentioned concept of critical periods in the development of the nervous system (Graf et al., 2021; Shonkoff et al., 2009). It seems that cognitive development can be stimulated through physical activity in children up to the age of 5, because during this period, the child's brain can develop spatial reasoning based on manual dexterity. Above this age, the relationship becomes non-significant, which means that these two branches of the child's functioning begin to exist more independently of one another. One can speak of a kind of sensitive period, characterized by increased susceptibility to interdependent influences. These findings are of particular importance to parents, educators and specialists working with children, who should pay attention to the development of gross and fine motor skills in relation to a child's cognitive deficits.

The question of whether the study provides arguments for the importance of physical activity in a child's mental development remains open. On the one hand, our results indicate that a higher level of manual dexterity in younger children is associated with a higher level of spatial reasoning. On the other hand, however, one cannot ignore the voice of specialists dealing with the development of motor training programs for preschool children, who point out that, although movement has a notably positive impact on the child's functioning, exercise programs should primarily take into account the child's emotional readiness and combine fun with elements of competition (Rajović et al., 2017; Teodorescu, Urzeala, 2020).

As far as the limitations of the present study are concerned, attention should be paid to the small sample size and the fact that the relationships were measured only once. In future research, it would be worth studying a larger sample and making several measurements so that the exact course of the mediation process could be observed. It is recommended that several measurements be compared in order to better estimate the actual causality, which is the basis of a mediation model (Kline, 2015). Moreover, the research was conducted on a sample of Polish children. It would be worthwhile to conduct this type of research outside Poland as well, in order to verify cross-cultural differences. In the future, it is also worth investigating whether fine motor skills mediate the relationship between aiming-catching skills and variables such as visuospatial memory, mathematics skills, and others. It would also be interesting to determine whether other aspects of gross motor skills (e.g. arm speed) determine the efficiency of fine motor skills and cognitive skills.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [K.D.], upon reasonable request.

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