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The interplay between pointing gestures and executive functions in early numeracy development: a longitudinal study

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Abstract
The role of fingers in early numerical learning has been extensively investigated, primarily focusing on how children use their fingers to represent quantities while solving arithmetic problems. However, less attention has been paid to the use of pointing gestures (i.e., the strategy of using fingers to mark or point to elements within a set during counting) among preschoolers, evaluating its interplay with domain-general cognitive precursors and its influence on the development of foundational early numeracy abilities for formal education, such as cardinality knowledge. To address this issue, a sample of preschool children was assessed through a longitudinal design, with the aim of evaluating both the unique contribution and the interplay of pointing gestures and domain-general precursors (i.e., working memory and inhibition) in the development of cardinality knowledge. Results showed that children with weaker inhibition benefit more from pointing gestures concurrently, while in the long term, children with stronger working memory skills gain a greater advantage from using pointing gestures to support their cardinality knowledge development. These findings highlight the interplay between domain-general cognitive factors and pointing gestures in supporting early numeracy development. Theoretical and educational insights for effective prevention practices are also discussed.

Keywords Finger use · Pointing · Early numeracy · Cardinality · Inhibition · Working memory

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Mathematics plays a fundamental role in our increasingly technological and number-based society, from facing everyday numerical situations to skilfully solving problems. Indeed, mathematical abilities at the beginning of formal schooling are important predictors of later academic and professional success, influencing individuals' wealth as well as national development and competitiveness (Bynner, 1997; Dougherty, 2003; Furlong et al., 2016; Gerardi et al., 2013; Rivera-Batiz, 1992). Yet early mathematical difficulties are on the rise, with the latest OECD-PISA report (OECD, 2023) highlighting a significant decrease in mathematical performance worldwide. In this context, it is crucial to identify the early precursors of mathematical learning and the strategies that children employ when tackling numerical problems, with the aim of enhancing their formal school readiness.

The present study examines the contribution and interplay of pointing gestures and cognitive abilities in the development of cardinality knowledge, using a longitudinal design with preschool-aged children. Pointing gestures are specific finger-use strategies used to indicate or mark elements within a set while counting. For example, when presented with a set of objects, children may use pointing gestures to touch or point to each item one by one in order to keep track of which items have been counted. While previous research has predominantly focused on children's ability to represent quantities using their fingers (Dupont-Boime & Thevenot, 2018), far less attention has been devoted to pointing gestures (Alibali & DiRusso, 1999; Gordon et al., 2021; Graham, 1999), with regard to how this specific finger use interacts with crucial components of executive functioning (EF) during the preschool period, such as working memory (WM) and inhibition. The present study seeks to address this gap by investigating how the use of pointing gestures, in interplay with EFs, is cross-sectionally and longitudinally associated with the acquisition of cardinality knowledge, a foundational numerical skill critical for children's formal mathematical learning (Geary & vanMarle, 2018; Geary et al., 2019). Our findings offer valuable insights into the role of pointing gestures and EFs in fostering early numerical learning, while also providing evidence that can be used to inform the development of tailored interventions for early numeracy enhancement in preschool years.

Domain-general precursors: the role of executive functions

Precursors of mathematical learning are defined as early abilities that temporally predict formal mathematical achievement (Passolunghi & Lanfranchi, 2012). Factors contributing to mathematical learning extend beyond the numerical domain, also involving environmental influences (such as educational and domestic practices) and cognitive antecedents (Aunio & Niemivirta, 2010). Concerning the latter, domain-general precursors refer to abilities that support learning across multiple areas, including intelligence, processing efficiency, and EFs (McLean & Hitch, 1999; Xing et al., 2022), with EFs representing the most extensively studied domain (Bull & Scerif, 2001; Bull et al., 2008). We use executive functioning as an umbrella term which encompasses all higher-order skills guiding complex, goal-oriented actions under novel and challenging conditions (Welsh, 2002). In one of the most influential models of adult EFs, Miyake and colleagues (2000) identify three distinct yet interdependent dimensions: (i) inhibition, defined as the suppression of automatic responses that are incongruent with the goal, (ii) updating, which involves monitoring incoming information and replacing irrelevant with newly relevant content, and (iii) flexibility, the ability to shift between tasks and adjust strategies accordingly. In a similar three-factor model, Diamond (2013) distinguishes inhibition, WM, and cognitive flexibility as the main EFs that start developing during early childhood.

This influential model regards WM as an EF, effectively replacing the updating function in Miyake and colleagues' (2000) framework. Subsequent research indicates that, while a three-factor model of EFs generally applies to school-aged children (Karr et al., 2018), a one-factor or two-factor model may better describe EFs in preschoolers. Typically, in these models, inhibition and WM load on separate factors, constituting two distinct latent dimensions (Miller et al., 2012; Monette et al., 2015; Usai et al., 2014). To date, although a debate regarding the factorial structure of EFs during preschool years remains open, WM and inhibition are the most extensively studied EFs in relation to mathematical learning (Emslander & Scherer, 2022).

WM is defined as a cognitive system responsible for storing and manipulating information of either visual or auditory nature, on a short-term time scale (Baddeley, 2000). Various theoretical models of WM have been proposed, ranging from modality-specific accounts (e.g., Baddeley & Hitch, 1974) to those suggesting a modality-independent structure (Engle et al., 1999). Among the most prominent modality-specific models of WM is Baddeley and Hitch's model (1974), which describes the WM system as consisting of a central executive component that manages attentional control processes, retrieves information from long-term memory and integrates information from two subordinate, modality-dependent components: the visuospatial sketchpad, which processes visuospatial information, and the phonological loop, which handles verbal information. Modality-independent models, on the other hand, classify WM involvement in a task on a continuum based on the attentional demand of the task, highlighting the degree of control that needs to be exerted to process relevant information and placing less emphasis on the perceptual modality in which such information is presented (see Engle et al., 1999, Engle, 2010). Beyond discrepancies in how WM is conceptualised, both cross-sectional and longitudinal studies highlight its strong association with early numeracy skills (Pellizzoni et al., 2025a; Bull et al., 2008; De Smedt et al., 2009; De Vita et al., 2022) and with mathematical learning during primary school (e.g., Viterbori et al., 2015). WM is also suggested to influence the use of mathematical strategies (Alibali & DiRusso, 1999; Dupont-Boime & Thevenot, 2018; Cragg et al., 2017b), supporting children in executing tasks more efficiently.

Alongside WM, inhibition, defined as the ability to suppress task-irrelevant distractors and inappropriate responses, also plays a major role in early numeracy and mathematical learning (Emslander & Scherer, 2022). Regarding the factorial structure of inhibitory processes, findings vary based on age, with a single-factor solution best fitting children aged 24 to 48 months (Gandolfi et al., 2014) and a two-factor model, distinguishing response inhibition from interference suppression, emerging in older children (Traverso et al., 2021). The association of inhibition with mathematical learning is well documented (Bull et al., 2008; Gilmore et al., 2015; Ng et al., 2015). For example, Ng and colleagues (2015) found that inhibition at age 4 predicted mathematical achievement at age 6. As would be expected, inhibition is involved during mathematical tasks mainly with regards to suppressing irrelevant information and execution of inappropriate strategies (Blair et al., 2008; Bull & Scerif, 2001; Cragg & Gilmore, 2014; Cragg et al., 2017a; Robinson & Dubé, 2013), with poor inhibitory skills constituting a risk factor for the development of mathematical difficulties (Espy et al., 2004).

Domain-specific precursors: cardinality knowledge and finger use

Domain-specific precursors are foundational abilities that emerge prior to formal schooling and predict performance within a particular learning domain. In the context of mathematics, these include skills such as counting, cardinality knowledge, and mental representation of the number line (Koponen et al., 2019; Mix et al., 2012)— universal core skills, in common with various other species (Rugani, 2018; Vallortigara et al., 2010). Beginning with these domain-specific precursors, mathematical abilities develop incrementally and cumulatively, leading to higher stability in mathematical performance and increasing individual differences over time (Aunola et al., 2002; Bast & Reitsma, 1997; Pellizzoni et al., 2024). Among domain-specific precursors, cardinality knowledge refers to an understanding of the function of counting, that is to determine the quantity of items in a set. Comprehension of this principle is particularly critical for later formal mathematical learning (Geary et al., 2018; Van Marle et al., 2014) and develops slowly through preschool and early primary school years (Geary & vanMarle, 2018; Geary et al., 2019). Evidence suggests that children achieve cardinality knowledge as they progressively master the well-known key counting principles described by Gelman and Gallistel (1986). Specifically, leading up to this achievement, they must learn that (a) one number word must be assigned to each object during counting, that (b) the total of items is unaffected by the order in which they are counted, and that (c) number words are pronounced in a fixed sequence. Only then, they can come to appreciate that (d) the final number in a counting sequence represents the total number of items in the set (Mix et al., 2012; Paliwal & Baroody, 2018)—the essence of the cardinality principle, which in turn allows children to grasp that (e) the counting process can be consistently applied to any set of objects. Mastery of the cardinality principle strongly accounts for individual differences in early numeracy and predicts later mathematical achievement during primary school (Geary et al., 2018; Van Marle et al., 2014). In addition to the acquisition of the counting principles, cardinality knowledge is also supported by domain-general precursors such as WM and inhibition, which help children manage the cognitive processes involved in this understanding (e.g., Li et al., 2024; Purpura et al., 2017). Specifically, evidence shows that WM helps children retain information about previously counted items, while inhibition allows them to avoid re-counting already counted items and to ignore other stimuli that may cause distraction, e.g. irrelevant features of the visual materials (Alibali & DiRusso, 1999; Gray & Reeve, 2014; Li et al., 2024; Graham, 1999). In this context, some authors have speculated that EFs may interact with the use of fingers during counting processes (e.g., Alibali & DiRusso, 1999; Gordon et al., 2021; Graham, 1999; see Fig. 1), potentially influencing the development of cardinality knowledge. However, to date, this hypothesis has been underexplored in empirical research.

Research has also consistently shown that children employ fingers when engaging in mathematical learning. Several studies have indicated that, during preschool and the early years of primary school, children use their fingers in various ways to support their mathematical performance (Alibali & DiRusso, 1999; Crollen & Noël, 2015; de Chambrier et al., 2018). Most studies have focused on instances where fingers serve a representational purpose, with children spontaneously producing a consistent sequence of finger patterns while engaging in counting and arithmetical tasks (e.g., showing the number "three" by extending the thumb, index and middle finger). Representational finger use strategies such as these are ontogenetically mature, as can be inferred by their involvement in adult numerical cognition (Badets et al., 2010; Di Luca et al., 2006; Domahs et al., 2010), with canonical finger configurations facilitating automatic access to semantic numeral knowledge (Di Luca & Pesenti, 2008). To date, research relating this kind of finger use to cognitive factors has mainly been conducted in the context of primary school arithmetic problem solving, where evidence indicates that children with stronger WM are more likely to use fingers (Dupont-Boime & Thevenot, 2018; Gathercole et al., 2004). Dupont-Boime and Thevenot (2018) found that six-year-olds with high WM capacity relied more heavily on representational

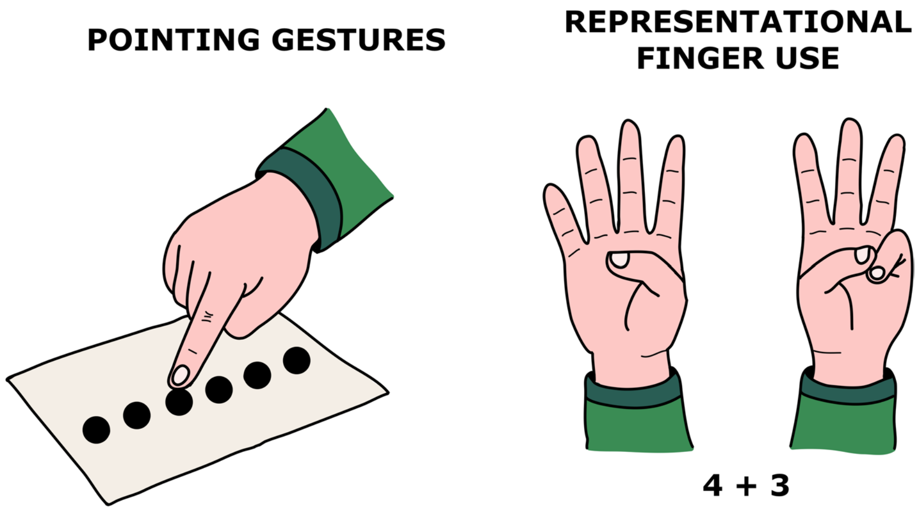

Fig. 1 Graphical representation of finger use in numerical tasks. Pointing gestures describe children's tendency to point at or touch each item in a set while counting. Representational finger use refers to using the fingers themselves to symbolize quantities during counting or arithmetic activities

finger use during addition tasks, and this strategy strongly correlated with better performance. By contrast, children with weaker WM may have found such representational finger use too cognitively demanding, in line with findings that these children are less likely to benefit from external supporting tools (Gathercole et al., 2006).

Comparatively, very few studies have investigated the use of pointing gestures and its relationship to children's cognitive abilities (Gordon et al., 2021). This common strategy involves using fingers to keep track of counted items, either by tagging or pointing to them, thereby helping children avoid double-counting or skipping elements and ensuring that each number word corresponds to a distinct element of the set (Alibali & DiRusso, 1999; Camos, 2003; Graham, 1999). For example, when a child is presented with a card displaying several printed items, they may use their finger to point to each item one by one while counting. This ontogenetically less advanced counting strategy is commonly observed in preschool years and has been found to improve counting accuracy not only in children, but also in nonhuman primates (Boysen et al., 1995). From a developmental standpoint, finger gestures are frequently observed in preschool children, who typically rely on a one-by-one counting strategy; nonetheless, they also appear in older children, adolescents, and even adults, when more sophisticated strategies, such as counting by grouping elements, are employed (Camos, 2003). Pointing gestures are particularly relevant within cardinality knowledge tasks, as they seem to assist children in assigning numerical meaning to each counted object (Alibali & DiRusso, 1999; Orrantia et al., 2022). Furthermore, several studies showed that finger gestures are associated with better cardinality knowledge due to better tracking of items during the one-to-one correspondence process (Alibali & DiRusso, 1999; Gordon et al., 2019, 2021). In a study by Alibali and DiRusso (1999), the authors found that the use of pointing gestures was associated with greater counting accuracy. Similarly, in a study by Gordon and colleagues (2019), the authors found that finger gestures were significantly associated with cardinality knowledge, suggesting that finger gestures may be linked to the acquisition of this skill. The use of finger gestures has also been included in several interventions aimed at promoting the acquisition of cardinality (Gibson et al., 2019; Mix et al., 2012; Orrantia et al., 2022). Alibali and DiRusso (1999) speculated that this type of finger use might be particularly common among children who need to employ such counting strategies to reduce the cognitive load of an excessively challenging task (contrary to what has been uncovered about the representational use of fingers in relation to WM capacity; Dupont-Boime & Thevenot, 2018). In this context, a recent cross-sectional study by Gordon and colleagues (2021) examined whether the relationship between finger gestures and cardinality knowledge was moderated by individuals' WM, but found that the interaction between WM and finger gestures was not statistically significant. Moreover, a recent systematic review by Gordon and Ramani (2021) emphasized that finger gestures interact with EFs in shaping numerical skills. However, to date, only one study has explored this interaction in relation to WM, and none have investigated it in relation to inhibition (Gordon & Ramani, 2021). Considering literature, examining both cross-sectional and longitudinal data could offer valuable insights into the role of cognitive factors (i.e., WM and inhibition) and their interplay with pointing gestures, ultimately contributing to our understanding of how these factors shape the development of cardinality knowledge.

Present study

As previous literature (see Alibali & DiRusso, 1999; Dupont-Boime & Thevenot, 2018) suggests a connection between finger use and cognitive factors, such as WM and inhibition (which typically influence the selection and effectiveness of mathematical strategies; Blair et al., 2008; Bull & Scerif, 2001), the aim of this study was to examine how domain-general cognitive factors and pointing gestures interact to influence the development of cardinality knowledge during the preschool period. Specifically, we investigated how cognitive skills, namely visuospatial WM and inhibition, interplay with pointing gestures, and how these factors are associated with the development of cardinality skills both cross-sectionally and longitudinally. Previous research has explored the influence of cognitive factors such as WM on representational finger use in arithmetic tasks (Dupont-Boime & Thevenot, 2018). In contrast, much less attention has been directed toward pointing gestures—i.e., the tendency to use fingers to tag or point to elements within a set, thereby facilitating one-to-one correspondence (Alibali & DiRusso, 1999; Gordon et al., 2019; Graham, 1999). While cognitive factors have been proposed to shape the use of pointing gestures in numerical contexts (Alibali & DiRusso, 1999), these hypotheses remain largely untested (Gordon et al., 2021). The present study is needed for several reasons. First, considering the established positive role of pointing gestures in the acquisition of cardinality (Gordon et al., 2019) and previous intervention studies promoting their use for developing cardinality understanding (Gibson et al., 2019; Mix et al., 2012; Orrantia et al., 2022), it is theoretically critical to evaluate whether these gestures support cardinality knowledge not only cross-sectionally but also longitudinally. Cardinality knowledge is recognized as one of the most significant developmental predictors of formal mathematical skills (Geary et al., 2018; Van Marle et al., 2014). In this context, incorporating an assessment of EFs will provide novel insights detailing how the frequency of pointing gestures may vary according to children's WM and inhibition levels. This approach addresses an underexplored research question, generating new insights into the relationship between executive functioning profiles and finger gestures. Second, from a practical perspective, finger gestures have been suggested to facilitate cardinality acquisition, yet existing research has primarily focused on cross-sectional designs (Gordon et al., 2019) or has embedded finger gestures within broader intervention programs (Gibson et al., 2019; Mix et al., 2012; Orrantia et al., 2022). Our findings will offer longitudinal evidence clarifying whether finger gestures sustainably enhance cardinality understanding over time while simultaneously considering children's executive functioning profiles, which are hypothesized to play a significant role in finger use (Alibali & DiRusso, 1999; Dupont-Boime & Thevenot, 2018; Gordon et al., 2021).

In this study, we chose to focus on visuospatial WM because of its close link to cardinality, both as a domain-general precursor of this skill (De Vita et al., 2022) and due to its potential role in supporting the use of pointing gestures for tracking counted elements (Gordon et al., 2021). As Alibali and DiRusso (1999) suggested, pointing gestures may reduce WM load compared to counting without tangible finger support. As for inhibition, this EF has been associated with the development of early numerical abilities, among which cardinality (Emslander & Scherer, 2022; Li et al., 2024), although its interaction with pointing gestures in fostering this development is yet to be explored. We focused on cardinality knowledge because it entails counting to determine the quantity of sets (Litkowski et al., 2020), inherently involving behaviours such as pointing gestures at early stages. Moreover, cardinality knowledge is a robust predictor of future formal mathematics learning (Geary & vanMarle, 2018; Geary et al., 2019), underscoring the importance of identifying the most relevant factors contributing to its emergence.

Based on this theoretical framework, we first hypothesised that both WM and inhibition would exhibit cross-sectional and longitudinal effects on the development of cardinality knowledge. Indeed, these cognitive skills are among the most studied precursors of early numerical abilities (for a review, see Emslander & Scherer, 2022). Second, we hypothesised that the use of pointing gestures would interact with these domain-general precursors in predicting the development of cardinality knowledge. Although prior research shows that WM is involved in representational finger use during arithmetic tasks (Dupont-Boime & Thevenot, 2018), the interaction between WM and the use of pointing gestures has been underexplored (Alibali & DiRusso, 1999; Gordon et al., 2021; Graham, 1999). Additionally, no studies have examined whether inhibition interacts with pointing gestures, despite the possibility that stronger inhibition may help children manage distracting stimuli during counting tasks (Gordon & Ramani, 2021). To date, research on the interplay between EFs and finger use has largely relied on cross-sectional data from preschoolers and primary school children (Alibali & DiRusso, 1999; Dupont-Boime & Thevenot, 2018; Gathercole et al., 2004; Gordon & Ramani, 2021). By adopting a longitudinal approach and focusing on younger participants, this study may offer new insights into how pointing gestures and cognitive factors interact to influence the development of cardinality knowledge. In doing so, it aims to provide a valuable contribution to understanding the foundations of early numeracy development.

Methods

Participants

As a first step, preschools were randomly selected from regional databases and the principals' consent was gathered to involve them in the research project. This selection process resulted in the enrolment of four preschools located in northeastern Italy. Participants were

110 middle-class children (as established by preschool records of socio-economic status) from the second and third preschool year. Some were excluded due to neurodevelopmental disorder diagnoses ($n=3$) or linguistic difficulties possibly hindering task understanding ($n=4$), resulting in a final sample of 103 children ($M_{age}=5.22$; $SD_{age}=0.55$; $Min_{age}=4.22$; $Max_{age}=6.16$; F = 53; M = 50).

Parents or legal guardians signed informed consent and data treatment forms, by which they were made aware of research aims and procedures. To ensure voluntary participation, children were told they could withdraw from assessment activities at any time. Additionally, any signs of distress led to immediate termination of the assessment session. As a token of appreciation, rewards such as stickers were given to the children after each session. The study was conducted in compliance with the Declaration of Helsinki and approved by the ethical committee of the University of Trieste.

Procedure

Testing was conducted individually and consisted of two 20-minutes sessions at a 5-month interval (T1 and T2). Measures administered sought to evaluate children's cognitive abilities, use of pointing gestures, and cardinality knowledge. Specifically, tasks assessing visuospatial WM, inhibition, and cardinality knowledge as well as pointing gestures during the cardinality knowledge task were administered at T1, while only cardinality knowledge was evaluated at T2.

Measures

Visuospatial WM

The visuospatial WM task was adapted from Lanfranchi et al. (2004). Children observed a sequence of movements performed by a frog in a 3 × 3 matrix and were then asked to recall it. The task began with a practice example, followed by four progressively challenging levels (as the number of movements to remember increased), each consisting of two equally difficult trials, for a total of up to eight sequences. The task was discontinued if both trials within the same level were performed incorrectly. One point was awarded for each correctly recalled movement within the matrix. Scores ranged from 0 to 28, with good reliability ($r=0.80$).

Inhibition

The Grass & Snow task (Carlson & Moses, 2001) was used to assess children's response inhibition. Two sheets of paper, one green and one white, were placed on the table in front of the children. The test consisted of two conditions, one congruent and one incongruent. In the congruent condition, children were instructed to quickly tap their hands on the green sheet when the experimenter said the word "grass" and on the white sheet when the experimenter said the word "snow". Then, in the incongruent condition children switched to tapping their hands on the white sheet for the word "grass" and on the green sheet for the word "snow". In both conditions, the words were pronounced by the experimenter in a pseudorandom order. Accuracy was recorded for each condition and a difference score was calculated (Score = Incongruent – Congruent), with total scores ranging from − 16 to 16. Test–retest reliability of this instrument was strong ($r=.73$).

Cardinality knowledge and pointing gestures

The Cardinality and Pointing Gestures Task was adapted from Le Corre and Carey (2007). Materials for the task consisted of ten cards, each presenting a display of identical drawings depicting familiar objects in quantities ranging from 1 to 10. The objects were distributed in haphazard arrays across the card. For each card, the experimenter first asked the children to count the objects (e.g., "Can you count the trees on this card?"). During the counting process, the experimenter also recorded whether children used finger gestures. One point was awarded for each item in which children were observed spontaneously using their fingers to indicate the depicted objects, either by pointing or by physically touching the card. In contrast, if children counted without pointing (e.g., by visually tracking the objects), no points were awarded (score range: 0–10). Then the experimenter, while covering the card, asked the children how many objects were depicted on the card (e.g., "So, how many trees are on the card?"). The reason for covering the card was to prevent children from counting again, as this would not be necessary if an understanding of the cardinality principle had occurred. One point was awarded if children stated the correct total (score range: 0–10). The instrument demonstrated good test–retest reliability ($r = 0.84$).

Results

Descriptive and bivariate correlations are shown in Table 1.

Bivariate correlations showed a negative statistically significant association of pointing gestures with visuospatial WM ($r = -.27$, $p < .01$), while a non-significant association emerged with inhibition ($r = -.03$, $p > .05$). Bivariate correlations also showed positive statistically significant associations between cardinality knowledge at T1 and both WM ($r = .38$, $p < .01$) and inhibition ($r = .30$, $p < .01$), but non-significant association with pointing gestures ($r = .01$, $p > .05$). Cardinality knowledge at T2 did not show statistically significant associations with either WM ($r = .12$, $p > .05$), inhibition ($r = .03$, $p > .05$) or pointing gestures ($r = -.04$, $p > .05$).

Hierarchical regression models

To assess the contribution of cognitive abilities (i.e., WM and inhibition), pointing gestures and their interaction to cardinality knowledge, two hierarchical regression models were

Table 1 Descriptive statistics and bivariate correlations between the variables included in the study

	M	SD	1	2	3	4
1. WM	15.20	6.99				
2. Inhibition	−1.41	3.15	.21*			
3. Pointing gestures	6.54	3.73	-.27**	-.03		
4. Cardinality (T1)	8.41	2.06	.28**	.30**	.01	
5. Cardinality (T2)	8.50	2.05	.12	.03	-.04	.43**

M = Mean; *SD* = Standard Deviation

*$p < .05$

**$p < .01$

specified, one cross-sectional and one longitudinal. First, for the cross-sectional model, cardinality knowledge at T1 was set as the dependent variable and predictors were introduced in four blocks, each controlling for school year. Block 1.1 evaluated the contributions of WM, inhibition, and pointing gestures; next, the interaction term between pointing gestures and WM (pointing gestures × WM) was added in Block 1.2; then, the interaction term between pointing gestures and inhibition (pointing gestures × inhibition) was added in Block 1.3. Finally, Block 1.4 simultaneously added both interaction terms to assess their contribution to cardinality knowledge at T1. The second hierarchical model followed the same structure as the first but with cardinality knowledge at T2 set as the dependent variable, controlling for the autoregressive effect of cardinality knowledge at T1.

To enhance interpretability, all continuous variables were standardised prior to analysis. The models' explanatory power was evaluated using R^2, which indicates the proportion of variance that is explained by the predictors. Additionally, simple slope plots were produced to further the interpretation of statistically significant interaction terms (Table 2).

Considering the cross-sectional hierarchical model, results from Block 1.1 showed that both WM ($\beta=0.249$, $t=2.402$, $p=.018$) and inhibition ($\beta=0.245$, $t=2.560$, $p=.012$) had positive, statistically significant associations with cardinality knowledge at T1. Block 1.2 results showed that the introduced interaction term pointing gestures × WM did not yield a statistically significant association with cardinality knowledge at T1 ($\beta=-0.071$, $t=-0.733$, $p=.465$); while the interaction term pointing gestures × inhibition displayed a negative, statistically significant association with cardinality knowledge at T1($\beta=-0.261$, $t=-2.428$, $p=.017$), as emerged in results from Block 1.3. In Block 1.4, the simultaneous introduction of both interaction terms revealed that only the pointing gestures × inhibition interaction yielded a negative, statistically significant association with cardinality knowledge at T1 ($\beta=-0.261$, $t=-2.297$, $p=.024$), while the pointing gestures × WM interaction did not reach significance ($\beta<-0.001$, $t=-0.004$, $p=.997$). In other words, given the negative effect size observed for the pointing gestures × inhibition interaction, results suggest that lower levels of inhibition are associated with a stronger positive association between pointing gestures and cardinality knowledge at T1 (see also the simple slope plot in Fig. 2).

Results from the longitudinal hierarchical model showed that neither WM ($\beta=-0.021$, $t=-0.203$, $p=.840$) nor inhibition ($\beta=-0.116$, $t=-1.216$, $p=.227$) in Block 2.1 predicted cardinality knowledge at T2, controlling for the autoregressive effect of cardinality knowledge at T1 ($\beta=0.469$, $t=4.793$, $p<.001$). In Block 2.2, introducing the pointing gestures × WM interaction term revealed a positive and statistically significant effect on cardinality knowledge at T2 ($\beta=0.212$, $t=2.321$, $p=.022$), while the pointing gestures × inhibition interaction term in Block 2.3 did not significantly predict cardinality knowledge at T2 ($\beta=-0.093$, $t=-0.848$, $p=.398$). Finally, results from Block 2.4 showed that, when both interaction terms were introduced simultaneously, only the pointing gestures × WM interaction yielded a statistically significant positive effect on cardinality knowledge at T2 ($\beta=0.259$, $t=2.731$, $p=.007$), whereas the pointing gestures × inhibition interaction did not reach statistical significance ($\beta=-0.185$, $t=-1.656$, $p=.101$). In other words, given the positive effect size of the pointing gestures × WM interaction, results suggest that higher levels of WM are associated with a stronger positive effect of pointing gestures on the development of cardinality knowledge at T2 (see also the simple slope analysis in Fig. 3).

Table 2 Hierarchical models evaluating the role of WM, inhibition, and their interactions with pointing gestures in cross-sectional (T1) and longitudinal (T2) cardinality knowledge. All models were controlled for school year, and the longitudinal models additionally controlled for the autoregressive effect of cardinality knowledge at T1 on T2

	β	SE	t	p	R^2
Cross-sectional hierarchical model					
Block 1.1					
Intercept	−0.014	0.151	−0.096	.924	0.145
WM	0.249	0.104	2.402	.018*	
Inhibition	0.245	0.096	2.560	.012*	
Pointing gestures	0.093	0.100	0.937	.351	
School year[a]	0.025	0.208	0.122	.903	
Block 1.2					
Intercept	−0.045	0.157	−0.288	.774	0.149
WM	0.253	0.104	2.433	.017*	
Inhibition	0.241	0.096	2.508	.014*	
Pointing gestures	0.108	0.102	1.060	.292	
Pointing gestures × WM	−0.071	0.096	−0.733	.465	
School year[a]	0.046	0.210	0.218	.828	
Block 1.3					
Intercept	0.008	0.148	0.058	.954	0.194
WM	0.238	0.101	2.349	.021*	
Inhibition	0.309	0.097	3.184	.002**	
Pointing gestures	0.097	0.097	0.996	.322	
Pointing gestures × Inhibition	−0.261	0.108	−2.428	.017*	
School year[a]	−0.029	0.204	−0.144	.886	
Block 1.4					
Intercept	0.008	0.156	0.054	.957	0.194
WM	0.238	0.102	2.331	.022*	
Inhibition	0.309	0.098	3.134	.002**	
Pointing gestures	0.097	0.100	0.971	.334	
Pointing gestures × WM	< −0.001	0.099	−0.004	.997	
Pointing gestures × Inhibition	−0.261	0.114	−2.297	.024*	
School year[a]	−0.029	0.208	−0.140	.889	
Longitudinal hierarchical model					
Block 2.1					
Intercept	−0.068	0.146	−0.464	.643	0.206
WM	−0.021	0.103	−0.203	.840	
Inhibition	−0.116	0.096	−1.216	.227	
Pointing gestures	−0.038	0.097	−0.391	.696	
School year[a]	0.119	0.201	0.589	.557	
Cardinality knowledge (T1)	0.469	0.098	4.793	< .001***	
Block 2.2					
Intercept	0.025	0.149	0.166	.868	0.248
WM	−0.038	0.101	−0.372	.711	
Inhibition	−0.108	0.094	−1.158	.250	
Pointing gestures	−0.083	0.097	−0.861	.391	

Table 2 (continued)

	β	SE	t	p	R^2
Pointing gestures × WM	0.212	0.091	2.321	.022*	
School year[a]	0.056	0.199	0.283	.777	
Cardinality knowledge (T1)	0.485	0.096	5.059	< .001***	
Block 2.3					
Intercept	−0.060	0.147	−0.409	.684	0.211
WM	−0.020	0.104	−0.191	.849	
Inhibition	−0.088	0.101	−0.873	.385	
Pointing gestures	−0.035	0.097	−0.358	.721	
Pointing gestures × Inhibition	−0.093	0.110	−0.848	.398	
School year[a]	0.100	0.203	0.491	.625	
Cardinality knowledge (T1)	0.448	0.101	4.444	< .001***	
Block 2.4					
Intercept	0.061	0.149	0.410	.683	0.269
WM	−0.039	0.100	−0.390	.698	
Inhibition	−0.051	0.099	−0.520	.604	
Pointing gestures	−0.087	0.096	−0.909	.366	
Pointing gestures × WM	0.259	0.095	2.731	.007**	
Pointing gestures × Inhibition	−0.185	0.112	−1.656	.101	
School year[a]	0.005	0.200	0.024	.981	
Cardinality knowledge (T1)	0.449	0.098	4.592	< .001***	

β = standardized coefficient value; SE = Standard Error; t = t-test statistic; p = p-value; R^2 = variance explained by the predictors in the model

[a]0 = second school year; 1 = third school year

*$p < .05$

**$p < .01$

***$p < .001$

Discussion

Given the predictive value of early numerical abilities for future formal mathematical learning (e.g., Aunola et al., 2004; Koponen et al., 2019; Nguyen et al., 2016), it is essential to refine our understanding of such skills, in terms of their developmental trajectories and associations with other factors, such as cognitive abilities and finger use. Thus, the aim of the present study was to investigate how domain-general precursors (i.e., WM and inhibition) relate to concurrent and longitudinal cardinality knowledge, examining their unique contributions and, more importantly, their interplay with pointing gestures. To date, research has primarily focused on the representational use of fingers as a strategy to enhance performance in numerical and arithmetic tasks (Crollen & Noël, 2015; de Chambrier et al., 2018), whereas the role of finger gestures and their interplay with EF remains largely underexplored (Alibali & DiRusso, 1999; Gordon et al., 2021). Given the theoretical framework, our research aimed to shed new light on the role of pointing gestures in both concurrent and longitudinal cardinality knowledge, exploring their potential interaction with WM and inhibition.

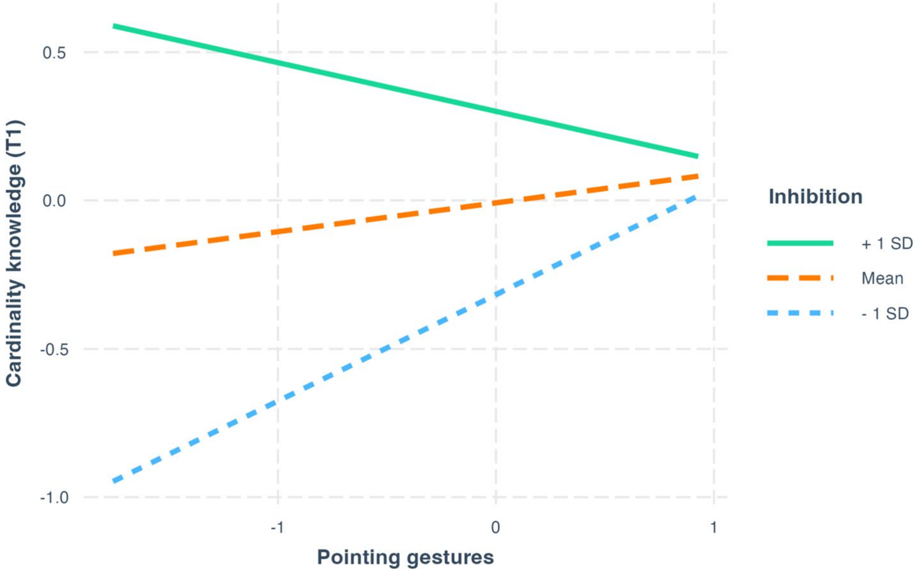

Fig. 2 Simple slope analysis: Graphical representation of the association between the interaction pointing gestures × Inhibition and Cardinality Knowledge at T1

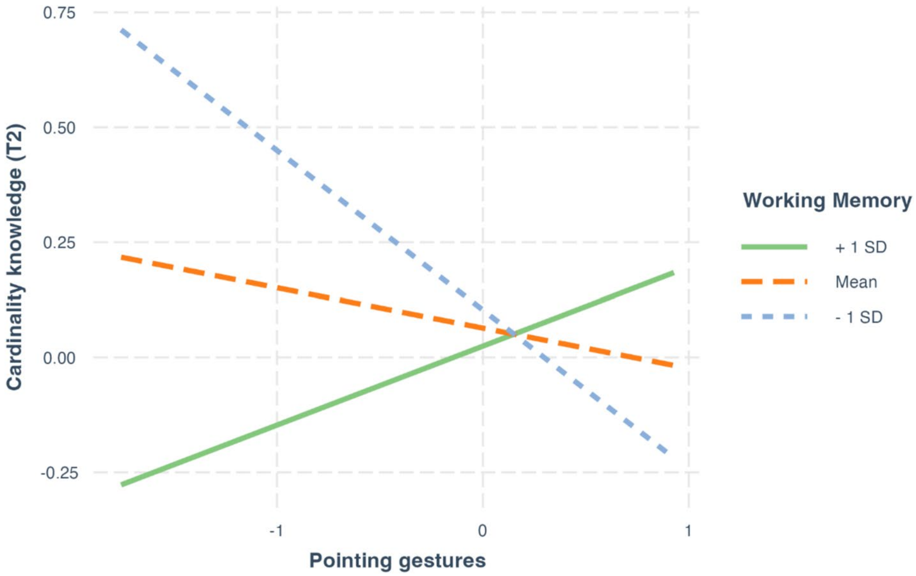

Fig. 3 Simple slope analysis: Graphical representation of the effect of the interaction pointing gestures × WM on Cardinality Knowledge at T2

We first hypothesised that both WM and inhibition would display cross-sectional and longitudinal associations with cardinality knowledge. Results from the cross-sectional hierarchical model revealed that both WM and inhibition had positive and statistically significant associations with cardinality knowledge assessed at T1, in partial agreement with our initial hypothesis and with previous literature (for a review see Emslander & Scherer, 2022). However, in the longitudinal hierarchical model, no apparent effects were observed for either WM or inhibition on cardinality knowledge at T2. These associations also did not emerge when examining bivariate correlations. Such results might be due to major maturational changes in EFs that occur during the preschool years, affecting both the development of WM and inhibition (for a review, see Nelson et al., 2016). Additionally, the contribution of domain-general cognitive factors to cardinality knowledge might be mediated by other domain-specific constructs (e.g., counting, digit recognition), which would play a more pronounced role in predicting this skill (e.g., Morosini et al., 2025; Krajewski & Schneider, 2009; Qi et al., 2023).

We also hypothesised that pointing gestures would interact with the domain-general precursors of WM and inhibition in predicting cardinality knowledge, both concurrently and longitudinally. In the cross-sectional model, the interaction term between pointing gestures and inhibition yielded a negative and statistically significant association with cardinality knowledge at T1. In other words, this pattern of results suggests that individuals with lower levels of inhibition tend to benefit more from pointing gestures during the cardinality knowledge task. Such finding aligns with our starting hypothesis and supports prior speculations (see Alibali & DiRusso, 1999; Graham, 1999). Specifically, using pointing gestures may serve as a particularly effective strategy for individuals with lower inhibition, as it allows them to track the elements of a set by offloading the cognitive burden of this process onto their fingers (Alibali & DiRusso, 1999). This finding provides the first evidence of the role of inhibition in moderating the association between pointing gestures and the acquisition of early numerical skills (Gordon & Ramani, 2021). However, contrary to our initial hypothesis, no statistically significant effect was found for the interaction between pointing gestures and WM on concurrent cardinality knowledge. This finding appears to replicate previous results observed in preschool samples, where no interaction was found between pointing gestures and WM in predicting cardinality knowledge (Gordon et al., 2021). Taken together, our findings suggest that children's levels of inhibition (rather than WM) may play a more central role in the association between pointing gestures, as an offloading strategy, and performance on the cardinality knowledge task (Gordon & Ramani, 2021).

On the contrary, results from longitudinal models showed that only the interaction term between pointing gestures and WM, and not inhibition, had a positive and statistically significant effect on cardinality knowledge development at T2. In other words, this finding indicates that individuals with higher WM levels showed a stronger positive association between pointing gestures and development of cardinality knowledge. These results suggest that pointing gestures yield more pronounced long-term benefits on cardinality knowledge for children with higher visuospatial WM. One possible explanation for this finding is that the combination of stronger WM and more frequent use of finger gestures may have a synergistic effect, enhancing children's likelihood of acquiring cardinality knowledge over time. To date, this is the first study to examine this interaction in a longitudinal design, strengthening the hypothesis that individuals with higher WM may use finger gestures more efficiently (Crollen & Noël, 2015; Gathercole et al., 2006; Lafay et al., 2013; Reeve & Humberstone, 2011), which in turn may increase their likelihood of acquiring early numerical skills over the long term. Turning to inhibition, results from the longitudinal hierarchical regression model showed no statistically significant interaction with pointing gestures in predicting cardinality knowledge development.

Although preliminary, these findings suggest that the role of finger gestures in the acquisition of cardinality knowledge should be interpreted in relation to both the specific EFs involved and the distinct patterns observed at cross-sectional and longitudinal levels. Inhibition appears to play a more prominent role cross-sectionally, moderating the effects of pointing gestures on cardinality knowledge, as individuals with lower inhibition may gain a stronger advantage from using fingers as an external cue (Alibali & DiRusso, 1999). In other words, finger gestures may serve as an offloading strategy for individuals with lower inhibition, offering short-term benefits by enhancing accuracy on the cardinality knowledge task. In contrast, the lack of a significant cross-sectional interaction effect involving WM (Gordon et al., 2021) suggests that inhibition may play a more prominent role in predicting the offloading patterns proposed in the literature (Alibali & DiRusso, 1999; Gordon & Ramani, 2021). Conversely, the longitudinal models, which assessed cardinality knowledge several months later, do not capture offloading behavior directly. Instead, they offer insights into how the interaction between EF profiles and frequency of pointing gestures may predict the development of cardinality knowledge over time. In this context, WM and finger gestures appear to have a synergistic positive effect on the long-term development of cardinality knowledge, suggesting that higher WM capacity combined with more frequent use of finger gestures may support early numeracy development over time.

Limitations and future perspectives

The results of this study should be interpreted considering some methodological limitations. Firstly, EF measures such as the Grass & Snow task are often affected by task impurity, as they impose a substantial cognitive load that encompasses multiple processes (Friedman & Miyake, 2004). Consequently, the task may have captured differences not only in inhibition but also in other EFs, such as flexibility (as children are required to shift from a congruent to an incongruent condition). Future studies should expand the evaluation protocol to include additional EF components, employing more comprehensive measurement models and testing their factorial structure.

Additionally, the present study only utilised two measurement sessions, with cardinality knowledge being the only measure assessed also at T2. Implementing a repeated-measures design with more than two sessions over an extended timeframe could uncover meaningful developmental trajectories, as the reciprocal roles of pointing strategies, domain-general, and domain-specific precursors may evolve in response to maturational changes in both EFs and mathematical abilities (Marzocchi & Valagussa, 2011). Such insights could support the design of tailored interventions for different developmental stages.

Further studies investigating developmental trajectories and antecedents of various mathematical skills are needed. Evidence suggests that even prior to formal instruction, mathematical cognition does not constitute a unitary learning domain but is instead multicomponential (Dowker, 2008). This study focused exclusively on cardinality knowledge, due to its relevance to pointing gestures. However, the mediating role of other domain-specific precursors should be explored, which may significantly influence the relationship between EFs and cardinality knowledge, both concurrent and prospective. Moreover, during test administration, we observed that some children tended to count aloud, while others counted silently. Future studies could further investigate this aspect and examine whether counting modality interacts with pointing gestures and EFs assessed in the present study. Another important aspect that should be considered in future studies concerns the instructional influence of teachers and parents. In this regard, it may be particularly valuable to administer questionnaires to parents and teachers to assess how frequently they observe pointing gestures in children and whether they encourage or explicitly teach finger use during numerical activities.

The observed interaction between pointing gestures and inhibition is particularly noteworthy, as it represents a novel contribution first highlighted in this article. Future research should aim to replicate our findings, as confirmation across independent samples is essential to strengthen validity and generalisability.

Conclusions

The results from this study provide novel evidence that the use of pointing gestures interacts with EFs to predict the development of cardinality knowledge. Specifically, children with lower inhibition benefit to a greater extent from using pointing gestures in a concurrent cardinality knowledge task, whereas those with higher WM derive greater long-term advantages from this strategy on cardinality knowledge development. These findings hold both theoretical and practical implications. From a theoretical perspective, they further confirm that early numerical learning may be shaped by a complex interplay between EFs and pointing gestures (Alibali & DiRusso, 1999; Gibson et al., 2019; Gordon & Ramani, 2021; Gordon et al., 2019, 2021). Specifically, our results show that the interplay between EFs and pointing gestures differently associates to concurrent and longitudinal cardinality knowledge, bringing novel insights into the role of EFs in pointing gestures (for a review see Gordon & Ramani, 2021). Our results have also some educational implications. First, our findings underline the importance of encouraging the use of pointing gestures during preschool years, both to provide children with an offloading strategy to help manage cognitive load of the task and to enhance cardinality knowledge over time. In particular, children with EF difficulties may benefit from more explicit and repeated instructions in the use of pointing gestures. Such instructions could be delivered by trained teachers during activities involving the counting of object sets, encouraging children not only to point to each item as they count (Mix et al., 2012), but also to use their fingers in a representational way (Gibson et al., 2019). In this regard, several interventions in the literature have incorporated pointing gestures into counting activities to enhance cardinality skills in preschool children (Gibson et al., 2019; Mix et al., 2012; Orrantia et al., 2022), finding positive results on cardinality knowledge development. Moreover, based on the positive synergistic effect found between finger gestures and WM on the development of cardinality knowledge in the present study, it may be beneficial to design programs that simultaneously target both domain-general precursors (Bull et al., 2008; Viterbori et al., 2015) and the encouragement of pointing gestures use (Orrantia et al., 2022), in order to maximize potential positive effects on the development of cardinality. Such interventions could facilitate early risk detection for mathematical learning disabilities and provide academic support to all children, not only through direct instruction (Passolunghi & Costa, 2016) but also by integrating effective strategies both within maths-specific contexts and across other learning domains.

Authors' contributions All authors contributed to both the research process and the writing of the manuscript. Material preparation, data collection and analysis were performed by Martina Taruscia, Alessandro Cuder, Carlotta Nordio and Sandra Pellizzoni. The work was drafted by Martina Taruscia, Alessandro Cuder, Carlotta Nordio and Sandra Pellizzoni. The work was critically revised by Martina Taruscia, Cuder Alessandro, Carlotta Nordio, Cinzia Chiandetti, Passolunghi Maria Chiara, and Sandra Pellizzoni. All the authors approved the version of the manuscript to be published and agree to be accountable for all aspects of

the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Data availability The data, materials, and code that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

Declarations

Ethics approval and consent to participate The study was conducted in compliance with the Declaration of Helsinki and approved by the ethical committee of the University of Trieste. Parents or legal guardians signed informed consent and data treatment forms, by which they were made aware of research aims and procedures.

Consent for publication The parents and legal guardians of the participants were fully informed about the use of their data for publication in a journal article. All parents and legal guardians provided written consent (through informed consent and data processing forms) for the publication of their children's data in this journal article.

Competing interests The authors declare no competing interests.

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Current themes of research:

In our laboratory, we investigate the development of mathematical cognition from preschool through secondary school, with particular emphasis on the cognitive and affective-motivational factors that influence mathematical performance and attitudes. The present work examines how pointing gestures (i.e., the tendency to use fingers to mark or point to elements within a set during counting) interact with children's cognitive profiles and how this interaction may affect the acquisition of early numeracy skills. Although this aspect remains underexplored in the current literature, it holds substantial theoretical and practical relevance.

Most relevant publications:

Cuder, A., Pellizzoni, S., Di Marco, M., Blason, C., Doz, E., Giofrè, D., & Passolunghi, M. C. (2024). The impact of math anxiety and self-efficacy in middle school STEM choices: A 3-year longitudinal study. *British Journal of Educational Psychology*, *94*(4), 1091–1108. https://doi.org/10.1111/bjep.12707.

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