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Research paper

Executive functions as predictors of learning prerequisites in preschool: A longitudinal study

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ABSTRACT

Introduction: This study focuses on 'learning prerequisites', cognitive and non-cognitive skills crucial for school success, often measured in preschoolers. Executive Functions (EF), like inhibition and cognitive flexibility, are vital among these prerequisites. While EF's role in early literacy and numeracy is acknowledged, some components are often overlooked.
Objective: The study aims to longitudinally explore the link between EF, assessed at the beginning of the preschool year and the learning prerequites, measured at the end of the same preschool year.
Method and Results: Evaluating 70 preschoolers (62.30 months, SD 4.55), results showed that certain EF measures predicted performance in literacy and numeracy tasks. Specifically, response inhibition predicted rhyme and syllable recognition, series completion, and cognitive flexibility predicted rhyme recognition. Moreover, EF, particularly response inhibition, correlated with overall metaphonology and pre-math abilities.
Conclusion: The findings suggest the importance of integrating EF enhancement in early educational interventions, aiding in selecting and optimizing EF skills crucial for later academic success.

1. Introduction

Learning prerequisites refer to a set of competencies that children develop before entering a school environment and that involve not only cognitive, but also linguistic, motor and emotional-behavioral aspects [1]. In preschools, among the most addressed learning prerequisites, phonological awareness (metaphonology) and numerical knowledge (pre-math) deserve attention by both educational as well as research fields.

Metaphonology and pre-math, considered proximal predictors of learning, are not directly tied to formalized instruction but rather rely on pre-existing cognitive processes, notably Executive Functions [2,3]. Executive Functions (EF) refer to a set of cognitive processes that facilitate goal-directed behaviors, including working memory, inhibitory control, and cognitive flexibility [4]. These processes enable individuals to adapt to new or challenging situations, regulate their thoughts and emotions, and make decisions that support successful outcomes. Therefore, defining the relationship between EF and learning prerequisites is crucial for future implications, including educational ones.

1.1. Learning prerequisites

Learning prerequisites are defined as a set of skills that a child develops before entering the school environment, facilitating more effective and enduring learning later [5,6]. These abilities are highly predictive of future academic success [see 1] and actively contribute to the school readiness of young children [7].

Literacy acquisition in children predominantly hinges upon the phonological pathway, a multifaceted process that entails the intricate interplay between written symbols and their corresponding sounds [8, 9]. Within this cognitive framework, children transform decoding graphemes into phonemes during reading and translate abstract symbols into meaningful auditory representations. Conversely, in writing, they engage in the reciprocal process, transcribing spoken sounds into written forms, thereby crystallizing their understanding of language structure and expression. The acquisition of reading and writing follows distinct competence stages: for instance, Frith's developmental stages model [10] outlines the progression from logographic to alphabetic, orthographic, and lexical stages.

The development of numerical skills precedes the ability to count, as

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children are predisposed to innate numerical knowledge and perception of approximate quantities [11]. Noteworthy among the explanatory models of mathematical acquisition is the theory of counting principles [12], positing that evolutionary drives enable the origin and full evolution of numerical knowledge. Additionally, the theory of different contexts [13] suggests that competence in counting mechanisms and the ability to use the symbolic language of the verbal and written numerical system depends on innate development as well as on environmental learning.

1.2. Distal and proximal learning prerequisites

Learning prerequisites can be classified into proximal or distal, which are closely interconnected [2,3]. Distal and proximal prerequisites differ in their temporal proximity to formal learning and their characteristic of being domain general or domain specific [14].

Proximal prerequisites are temporally closer to the transition moment to primary school and simultaneously represent a more domain-specific aspect. Indeed, they refer to the specific abilities and information that children must acquire before moving on to a higher-level skill or knowledge area. In most preschools, at the end of the final year, a great deal of attention is paid to phonological awareness (metaphonology) and numerical knowledge (pre-math) among the prerequisites for proximal learning. Since children have now developed language skills, emphasis is placed on the ability to work phonologically on verbal mental representations and the ability to recognize numbers visually and verbally [15]. Consistently, metaphonology turns out to be one of the most predictive skills for reading and writing at school age, just as numerical knowledge turns out to be crucial for learning mathematics [16].

Distal learning predictors, on the other hand, include the fundamental information and abilities that children must acquire early in life in order to support the subsequent acquisition of more complex abilities. They are temporally far from the transition to primary school and represent a broader domain not based on formalized instruction, but referring to already acquired processes such as motor skills, early language competencies and cognitive abilities, among which Executive Functions [2,3].

Executive Functions (EF) is an umbrella term for higher-level, top-down mental processes that are deliberately controlled and strategically used by the subject. These processes are necessary for an individual's physical and psychological health, as well as cognitive, social, and psychological development [4]. It is generally agreed that EF develops from infancy through late adolescence [17–20], with the preschool years identified as a period of particularly rapid and sensitive development [21,22]. Furthermore, several recent studies indicate that the structure of EF varies with age [23,24] and there is significant debate regarding whether in early ages of development EF constitutes a single ability or distinct, yet interrelated, multiple abilities [25]. Some studies suggest that in preschool age EF is mostly unidimensional [23,26] although others found a bidimensional structure [27–29] and some authors suggest that still in the preschool years the basic EF components (i.e. inhibitory control, working memory and cognitive flexibility) begin to differentiate [30,31]. However, even though empirically preschool EF measures could represent a unitary or bi-factor construct, conceptually, in a developmental perspective, the different emerging basic EF components must be taken into account, as they can all contribute to the EF structure, either unitary or multiple. Consistently, even those studies propending for a unitary solution found that one EF factor could not account completely for the inter-subjects variability (e.g. [26]), result that is compatible with the hypothesis that the basic EF components are emerging, although visible in later ages. Furthermore, the need to keep different basic EF measures may be particularly relevant when investigating the relation with those cognitive and learning domains that typically develop in later stages, such as school age, when a EF multiple structure is found consolidated [32].

Specifically, inhibitory control (IC) is defined as the ability to control one's actions, behavior, emotions, and attention with the aim of doing something appropriate or necessary, ignoring external or internal temptations [4]. IC consists of two components: response inhibition (RI), which is the capacity to inhibit automatic responses in order to promote new and context-appropriate responses, and interference control (IC), which is the ability to minimize interfering stimuli while maintaining attentional focus on a predefined target stimulus. Working memory (WM) enables to hold, manipulate and update information in mind during the execution of complex tasks [33,4]. Cognitive flexibility (CF) allows us to modify thoughts, responses, cognitions, and attention when facing changing contexts. It enables one to choose whether to implement one behavior over another and decide when switching between tasks [4, 34].

EF are not only implemented when faced with structured, cognitively demanding tasks, but are also required in everyday tasks in the context of everyday life. For this reason, the executive domain can be assessed either through performance-based tasks that are more experimental and laboratory-based or through questionnaires filled out by parents and teachers assessing the child's executive behavior enacted in routine challenges [35]. However, while performance-based assessments show the effectiveness of performance in the most favorable setting, behavioral rating scales show the frequency of goal accomplishment in everyday settings [36]. Consistently the literature reports discrepancies between EF rating scales and performance-based assessments [36], suggesting including both assessment modalities to have a complete understanding of EF functioning [37]. This combined approach ensures a more accurate and comprehensive evaluation of EF, capturing both the potential and actualization of EF in diverse contexts.

1.3. EF predicting learning prerequisites

Understanding the relationship between EF, metaphonology, and pre-math skills is of interest for researchers, educators, and global initiatives on early education, given that they serve as precursors for later academic success [38]. However, while the strong connection between EF and formal learning, such as text comprehension [39], writing [40], and mathematics [41] during school age, is well-established, there is considerably less understanding of the relationship between EF and learning prerequisites e.g., [26]. This pertains specifically to the early stages of literacy and numeracy development before formal reading and math instruction takes place.

It is worth noting that EF can support learning prerequisites, operating on both cognitive and behavioral dimensions [42]. All EF basic components can be crucial for specific learning prerequisites e.g., [43–47]. A few studies have analyzed the contribution of inhibitory control to pre-literacy skills in preschoolers with inconsistent results e.g., [48,49]. For instance, Becker et al. [50] found a significant correlation between letter-word recognition, children's vocabulary, and inhibitory control in 53–80-months-old children. Strong inhibitory control, working memory and behavioral self-regulation skills were identified as crucial for these literacy prerequisites development. The study suggested that these skills enhance the processing and retention of letter-related information during activities such as letter copying and learning letter names and sounds, indicating a potential synergistic interaction as reading abilities evolve. Additionally, working memory was found to be highly correlated with phonological awareness [51] as well as to predict changes in vocabulary during the preschool years, but not in print-related abilities [52]. In addition, several studies showed that cognitive flexibility was linked to various aspects of literacy, including vocabulary and print knowledge [53,52] but not to definitional vocabulary nor phonological awareness [54].

Several studies also showed associations between EF and pre-math in preschool children [44,55]. Findings are relatively consistent across studies in showing how inhibitory control is a strong predictor of pre-math skills e.g., [43,56]. For instance, McClelland et al. [52]

emphasized that inhibitory control plays a crucial role in helping children develop the learning-related behaviors needed for early math skills, such as perseverance and sequential problem-solving abilities. Many studies in preschool age showed that working memory predicted pre-math abilities e.g., [57,58]. Specifically, Purpura & Ganley [54] underlined that working memory was a significant predictor of three pre-math skills, namely cardinality (counting a subset), set comparison, and number order, which are commonly regarded as among the most robust predictors of future success in math [59]. Regarding cognitive flexibility, few studies investigated its relationship with pre-math. For example, Lan et al. [58] found that cognitive flexibility was related to both counting and calculation, by facilitating the adaptation of strategies and approaches when encountering different types of math problems or concepts.

It is important to point out some gaps in the literature. Firstly, many of the cited studies used a cross-sectional design that, due to the great inter-individual variability, are weak for evolutionary approaches. Furthermore, most of the studies evaluated only one component of EF at time, usually working memory or inhibitory control e.g., [57,50,51,60], thus missing to define the contribution of EF basic components in learning prerequisites. Furthermore, given the emergence of different EF components in preschool, it becomes crucial to take into account the collective role of all these components. Consistently, most studies do not consider the role of EF in the everyday context, mainly using EF performance-based tasks while neglecting the importance of including EF indirect measures filled out by children's adult referees. In fact, it must be noted that for school readiness, there is a need for behaviors that align with the school environment and are tied to a child's self-regulatory skills. These behaviors encompass maintaining focus in class, resisting distractions, completing tasks, and adhering to task rules [61,62], all dimensions that refer to executive behavior rather than specific EF basic components.

Additionally, the existing literature investigated the relationship between EF and metaphonology and between EF and pre-math separately, thus overlooking the natural interplay between literacy and math acquisition, especially when general domain underpinnings are considered. In fact, especially in preschool ages, learning prerequisites represent a multi-componential construct which is still developing and deserve to be fully investigated e.g., [26,60].

To the best of our knowledge, a few studies investigated the relationship between different components of EF and both metaphonology and pre-math [26,52,58]. Fuhs et al. [26] measured the three basic EF components (i.e., inhibitory control, working memory, and cognitive flexibility) at the beginning of preschool in order to evaluate their predictive role on oral comprehension and letter–word identification, and pre-math skills, specifically applied problems, quantitative concepts at the end of preschool. The results showed that a unique factor of EF, was a strong predictor of gains in mathematics and a moderate predictor of language gains in kindergarten. Furthermore, McClelland et al. [52] examined the predictive roles of behavioral self-regulation, inhibitory control, working memory, and cognitive flexibility in relation to letter-word identification, picture vocabulary, and applied problems. They found that behavioral self-regulation played a significant role in early academic success, particularly showing the strongest correlations with advancement in achievement during kindergarten and connections to emerging mathematical skills. Additionally, Lan et al. [58] investigated the predictive roles of inhibition, working memory, and attentional control in relation to applied problems and letter-word identification in a US sample, showing the significant role of working memory, inhibition, and attentional control. However, it is important to note that both studies by McClelland et al. [52] and Lan et al. [58] relied solely on single measures to assess pre-math and emergent literacy skills, which should be acknowledged as a limitation.

Based on the literature background conducted, this study tries to fill the remaining open gaps. Specifically, it aimed to investigate the role of all EF basic components, including inhibitory control, working memory, and cognitive flexibility, in addition to executive functioning at the behavioral level on both metaphonology and pre-math. Consistently, a longitudinal design was used in the last year of preschool, as this period represents the peak of school readiness development.

2. Method

2.1. Participants

The sample of this study included 70 typically developing preschool children with an average age of 62.30 months (SD 4.55; months range: 53–71), attending 14 kindergarten classes in Tuscany, Italy. The sample size was estimated according to the existing literature (sample size ranging from 50 to 129; [48,50,51,54,55]) and verified on the basis of a power analysis (GPower: power level=0.90, f^2= 0.25, α=0.05, estimate sample size=72). The sample consisted of 32 males and 38 females and presented diversity in terms of language exposure (32.9 % were exposed to at least one language other than Italian), cultural background (17 mothers and 12 fathers were not Italian), and parents' educational level. Specifically, 2 mothers and 3 fathers had an elementary licence, 12 mothers and 26 fathers had a middle school degree, 29 mothers and 33 fathers had a high school diploma, and 25 mothers and 5 fathers had a university degree.

The average Socioeconomic Status of the sample, calculated by adding the education level of both mothers and fathers (from 2 - both with elementary licences - to 8 - both with university degree) and their employment status (employed: 1; unemployed: 0), was 7.46 (SD 1.57) with a range of 3–10.

To ensure that the examined sample was typically developing, in addition to historical data collected through a questionnaire given to parents (e.g., "Do your children have a developmental difficulty such as language impairment, cognitive disorder etc."), cognitive development was investigated using the Raven's Coloured Progressive Matrices test (CPM; [63]). CPM scores ranged from 11 to 32 with a mean of 19.84 (SD 4.72) and were within the normal range for age (< 2 SD from the mean) according to the normative data of the Italian sample.

2.2. Study design and procedure

The present study has a longitudinal design since EF, considered as predictors, were assessed at the beginning of the last preschool year (in October and November 2021) and the learning prerequisites, considered as outcome measures, were assessed at the end of the same year (in May and June 2022).

It is important to underline that during the academic year 2021/2022, there were many restrictions in the Italian context due to the spread of the Covid-19 virus. This caused, for the present study, the inability of the psychologists involved to enter schools to conduct the assessments. For this reason, the EF assessments were automated through the use of Gorilla.sc web platform accessed via the Internet on a tablet with which the child interacted under the supervision of a teacher from the school involved in the project. All the EF tasks were administered in a single session. The learning prerequisite tests, on the other hand, were conducted remotely: the child was connected via a Google Meet platform with the psychologist administering tests. The same teacher sat next to the child to monitor the child's physical safety. Both assessments for all children were conducted in the school setting in a quiet room carefully selected to be entirely dedicated to this study. In order to guarantee a proper setting for remote assessment, researchers involved in the study were trained to follow the recommendations proposed by Ruffini et al. [64] in a systematic review on remote cognitive assessment in developmental ages. Furthermore, the assessment sessions were supervised by a teacher responsible for ensuring the child's physical safety and addressing any technological issues that might arise.

2.3. Instruments

Two instruments standardized in the Italian context and widely used for the assessment of metaphonology and pre-math were selected.

To assess metaphonology, the CMF [65] standardized Italian battery for the assessment of metaphonological skills was used. From the battery, the following two subtests were used:

- Rhyme recognition: among various options, children are required to indicate the word that rhymes with the given one. The correct answers (0 to 15) were evaluated;
- Initial syllable recognition: children are asked to recognize, among a series of given words, the one that begins with the same syllable as the word initially listed. The correct answers (0 to 15) were evaluated.

Based on these two subtests, by adding up the number of correct answers to both, a Metaphonological Total Index (0 to 30) was calculated.

To assess pre-math, the BIN 4–6 [66] standardized Italian battery for the assessment of pre-math was used. Children were administered the following subtests:

- Number name matching: children are asked to recognize the number (in symbols) that is pronounced. The correct answers (0 to 9) were evaluated.
- Comparison of Arabic numbers: children are asked which number is greater in a pair. The correct answers (0 to 11) were evaluated.
- Seriation of Arabic numbers: children are asked to put numbered cards in order. The correct answers (0 to 5) were evaluated.
- Series completion: children are asked to complete a sequence of numbers. The correct answers (0 to 6) were evaluated.

In order to have a synthetic score of math abilities, in agreement with the procedure suggested by the Authors of the BIN 4–6 [66], a Pre-math Total index (0 to 31) was calculated by adding up the number of correct answers of the four tests.

To assess Executive Functions five tasks and a questionnaire were administered.

- The Go-NoGo task [62] evaluated response inhibition, requiring children to touch the screen when a target stimulus (Go stimulus) appeared and refrain from touching for a non-target stimulus (No-Go stimulus). The test presents 3 sets of 25 items with 30 % Go stimuli. The final score ranged from 0.00 to 1.00 as it was calculated by multiplying the proportion of correct responses out of the total Go responses by the proportion of correct responses out of the total NoGo responses (for a similar scoring procedure see Howard et al., 2020).
- The Flanker task [62] was used to evaluate interference control. It consists of five aligned stimuli on the screen. Children were asked to indicate the direction of the central arrow by tapping the corresponding point. Correct responses for incongruent items (Flanker CR, 0 to 26) were recorded.
- The MrAnt task [62] assesses visuospatial working memory. This test uses the outline of a personage (an Ant) on which coloured dots were simultaneously superimposed. The number of dots ranged from 2 to 6, corresponding to 5 levels of span. Each level had 3 consecutive items. The answer was considered correct when the child identified the positions of all dots of an item. The test was interrupted when a child failed all three items of a given level. Regardless of the number of dots, one point was assigned when a child got at least two out of three items correct, and one-third-of a point when only one item was correct. If the child pointed to a greater or a lower number of dots, the answer was considered wrong. The scores ranged from 0 to 5 (MrAnt CR, 0 to 5).
- The Dimensional Change Card Sort [62] task assesses cognitive flexibility. Children categorized cards based on color, shape, and shifted between these rules following a specific criterion. The total number of correct responses (DCCS CR, 0 to 24) were recorded.
- The Preschool Executive Functions Questionnaire [67] was utilized to assess EF skills in daily life. Parents responded to 24 items evaluating children's self-regulatory abilities in behavioral, cognitive, and socio-emotional domains on a scale from 1 (not at all) to 5 (very much) (QUFE ranging from 24 to 120).

2.4. Statistical analysis

Descriptive analyses (mean, standard deviation, skewness and kurtosis) were conducted on metaphonology, pre-math and EF measures.

Correlation analysis was performed to assess the relationship between all measures.

Multivariate regressions were conducted to assess which EF predicted metaphonological and pre-math abilities putting EF measures (GoNoGo RC, Flanker RC, MrAnt RC, DCCS RC, QUFE) as predictors and each metaphonological and pre-math abilities as outcome variables (Rhyme recognition, Initial syllable recognition, Number name matching, Comparison of Arabic numbers, Seriation of Arabic numbers and Series completion).

Two multivariate regression analyses were performed to investigate which EF could predict metaphonological and pre-math abilities with EF measures (GoNoGo RC, Flanker RC, MrAnt RC, DCCS RC, QUFE) as predictors and metaphonological and pre-math indices as outcome variables.

3. Results

The descriptive analyses of the scores (mean, standard deviation, minimum-maximum range) of the variables under examination are reported in Table 1. All variables were normally distributed [68].

All children completed all measures at both time points, except for two children who were not available to perform the metaphonology tests and two children whose parents did not fill out the questionnaire.

From the correlation analysis (Table 2), GoNoGo CR significantly and positively correlated with both metaphonology index and pre-math index and with all subtests of metaphonology index and of pre-math index, except from the number name matching subtest. Flanker CR

Table 1
Descriptive analysis of metaphonology, pre-math, and EF scores.

	Variables	N	Mean (SD)	Min-Max
Metaphonology	Rhyme recognition	68	10.22 (3.86)	2–15
	Initial syllable recognition	68	10.78 (3.33)	2–15
	Metaphonology Total index	68	21 (6.2)	5–30
Pre-math	Number name matching	70	8.5 (1.2)	3–9
	Comparison of Arabic numbers	70	10.03 (1.77)	3–11
	Seriation of Arabic numbers	70	4.17 (1.65)	0–5
	Series Completion	70	4.33 (1.43)	0–6
	Pre-Math Total index	70	27.01 (4.56)	14–31
Executive Functions	GoNoGo CR	70	.8 (0.17)	.18–1
	Flanker CR	70	11.27 (7.91)	0–26
	MrAnt CR	70	1.62 (1.14)	0–3.33
	DCCS CR	70	17.8 (2.27)	10–23
	QUFE	68	95.29 (10.79)	65–120

CR (correct responses).

Table 2
Correlations between measures of metaphonology, pre-math, and EF.

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Rhyme recognition	–												
2. Initial syllable recognition	.482**	–											
3. Metaphonology index	.882**	.838**	–										
4. Number name matching	.168	.296*	.264*	–									
5. Comparison of Arabic numbers	.266*	.249*	.300*	.450**	–								
6. Seriation of Arabic numbers	.178	.190	.213	.528**	.410**	–							
7. Series Completion	.228	.180	.239*	.285*	.437**	.393**	–						
8. Pre-Math index	.284*	.300*	.339**	.719**	.792**	.783**	.701**	–					
9. GoNoGo CR	**.308***	**.383****	**.398****	.228	**.270***	**.240***	**.316****	**.351****	–				
10. Flanker CR	.216	.202	**.244***	.056	.061	.035	.009	.054	.256*	–			
11. MrAnt CR	.091	.120	.121	.052	.056	.215	**.256***	.194	.164	.151	–		
12. DCCS CR	**.334****	.115	**.270***	.185	.059	.187	.087	.167	.159	−0.044	.141	–	
13. QUFE	−0.071	−0.082	−0.088	.066	.172	.055	−0.028	.095	.188	.070	.094	−0.035	–

CR (correct responses), ** $p<.01$, * $p<.05$; in bold the significant relations between EF measures and metaphonological/pre-math abilities.

correlated with the metaphonology index, Mr Ant CR correlated with the series completion subtest and DCCS CR correlated with rhyme recognition and metaphonology index.

From the multivariate regression with EF (GoNoGo RC, Flanker RC, MrAnt RC, DCCS RC, QUFE) as predictors and metaphonological subtests (Rhyme recognition, Initial syllable recognition) as outcome variables, GoNoGo RC ($F(2,59)=5.01$, $p=.01$) and DCCS RC ($F(2,59)=3.6$, $p=.034$) have a significant role in the models. Specifically, GoNoGo RC ($t = 2.16$, $p=.035$) and DCCS RC ($t = 2.57$, $p=.013$) significantly predicted rhyme recognition and GoNoGo RC ($t = 3.04$, $p=.003$) significantly predicted initial syllable recognition (see Fig. 1).

From the multivariate regression with EF (GoNoGo RC, Flanker RC, MrAnt RC, DCCS RC, QUFE) as predictors and pre-math subtests (Number name matching, Comparison of Arabic numbers, Seriation of Arabic numbers and Series completion) as outcome variables, GoNoGo RC approached the significance in predicting comparison of arabic numbers ($t = 1.87$, $p=.067$) and significantly predicted series completion ($t = 2.55$, $p=.013$). MrAnt RC approached the significance in predicting series completion ($t = 1.98$, $p=.052$) (see Fig. 2).

From the multivariate regression performed with EF measures (GoNoGo RC, Flanker RC, MrAnt RC, DCCS RC, QUFE) as predictors and total metaphonological and pre-math indices as outcome variables, GoNoGo RC ($F(2,59)=5.82$, $p=.005$) has a significant role in the model. Specifically, GoNoGo RC significantly predicted both metaphonological ($t = 3.05$, $p=.003$) and pre-math ($t = 2.3$, $p=.025$) indices (see Fig. 3).

Results of all regression models indicated medium effect sizes as assessed by eta-squared, suggesting a moderate degree of association between the variables under study.

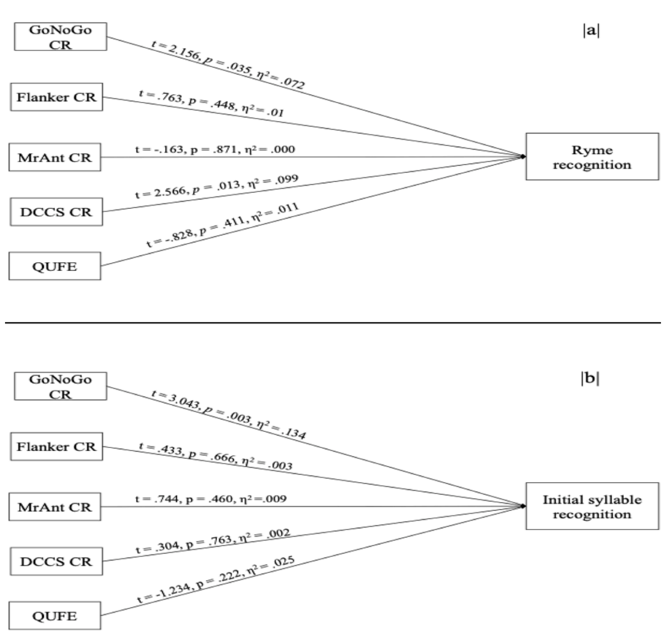

Fig. 1. Regression models with EF measures as predictors and metaphonological subtests as outcome measure.
For each predictor, t value, p value and effect size (small ≥ 0.01, medium ≥ 0.06, large ≥ 0.14) are indicated.

4. Discussion

The aim of the current study was to investigate how different dimensions of Executive Functions (EF) predict metaphonology and pre-math in the last year of preschool. This is a longitudinal study because EF, considered as predictors, were assessed at the beginning of the last year and the learning prerequisites were evaluated at the end of the same year. This study adds to the literature by investigating the relationship between learning prerequisites and EF by taking into account a considerable number of EF components, in line with fractional models of EF, but also executive behavior, as it could be relevant for predicting school readiness. Additionally, both metaphonology and pre-math components were simultaneously investigated, highlighting importance to both of these abilities that fall within the prerequisites of learning and represent the closest underlying abilities to school learning.

Seventy 5- to 6-year-old children participated in this study and were assessed for both learning prerequisites and EF using standardized tests and an EF questionnaire. EF were measured with the GoNoGo task assessing response inhibition, the Flanker task for interference control, the Dimensional Change Card Sort Test for cognitive flexibility, the MrAnt test for working memory and the QUFE questionnaire to indirectly investigate EF functioning in daily life.

Regarding the relationship between metaphonology and EF, correlational analysis showed that the metaphonology index was positively correlated with inhibition, interference control and cognitive flexibility. At the same time, initial syllable recognition positively correlated with response inhibition and rhyme recognition correlated with both response inhibition and cognitive flexibility. In particular, response inhibition emerged as a significant predictor of initial syllable recognition, while in conjunction with cognitive flexibility, it demonstrated predictive power for rhyme recognition. The findings of this study align with the study of Gandolfi et al. [48], which demonstrated a strong relationship between inhibition and syllable and rhyme recognition. One plausible explanation for the central role of inhibition is that a high score in response inhibition enables children to effectively respond and recognize syllables by suppressing signals that could lead to impulsive responses, such as confusing similar letters. Additionally, inhibition is pivotal in rhyme recognition, as children need to identify the sound of a word and associate it with another word sharing a phoneme, disregarding alternative options [48]. Consistently, effective response inhibition helps children filter out non-rhyming words or irrelevant

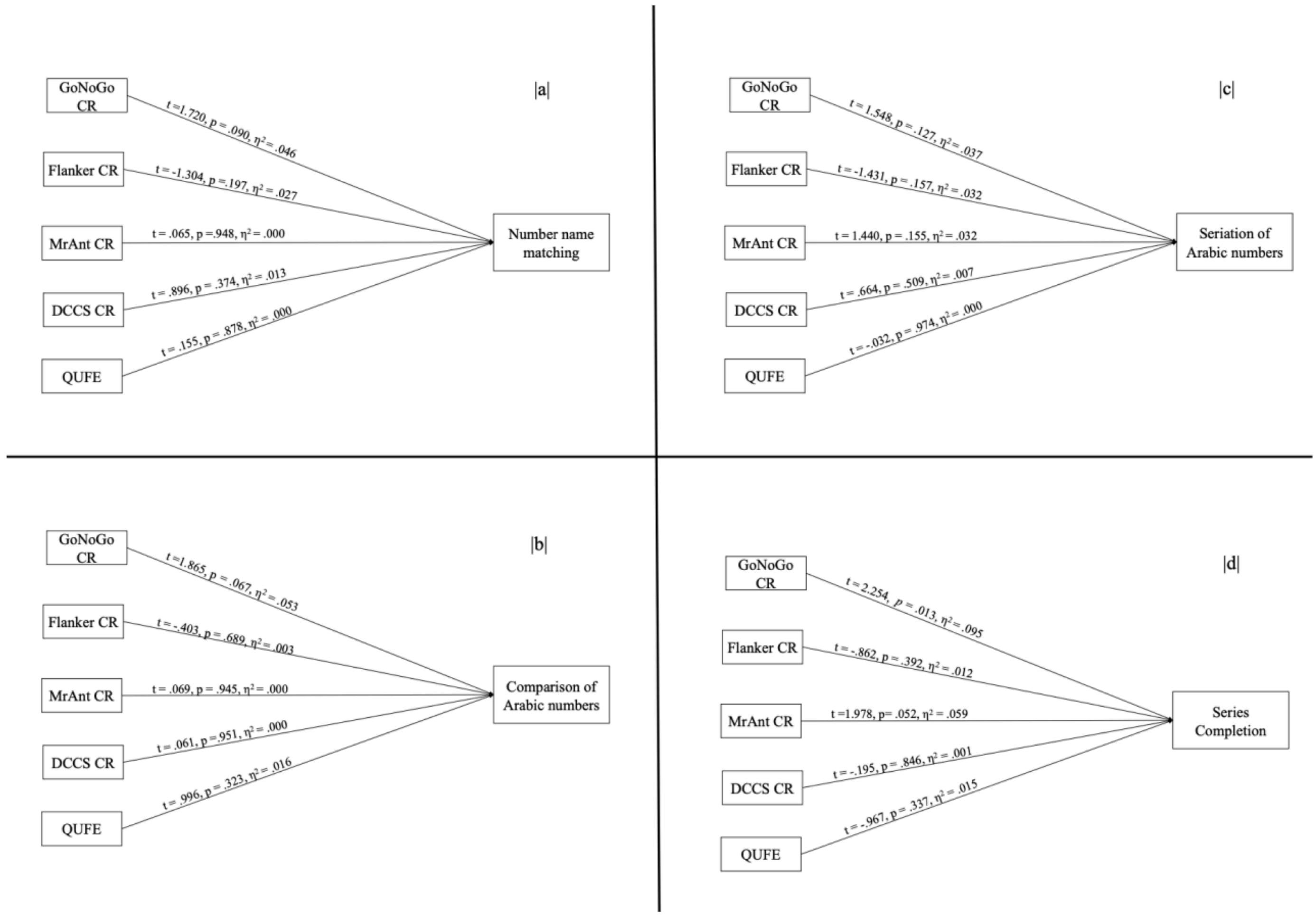

Fig. 2. Regression model with EF measures as predictors and pre-math subtests as the outcome measure.
For each predictor, t value, p value and effect size (small $\geq$ 0.01, medium $\geq$ 0.06, large $\geq$ 0.14) are indicated.

phonetic cues, allowing them to concentrate on the critical aspects of the task. Moreover, it plays a role in the suppression of semantic associations that do not contribute to rhyme recognition. When the child encounters words with similar meanings but different phonological structures, inhibitory skills help prevent these semantic associations from interfering with rhyme identification. At the same time, the role of cognitive flexibility in predicting rhyme recognition deserves attention. It likely plays a crucial role in facilitating the mental processes involved in identifying and categorizing words based on their phonetic similarities. When confronted with a rhyme recognition task, children must not only recognize the phonetic pattern shared by words but also be flexible in their approach to identifying such patterns across diverse word sets. Cognitive flexibility enables individuals to quickly adjust their attention and processing strategies, allowing them to recognize rhymes even in novel or varied contexts, by switching between different phonemic patterns and word associations. Therefore, the combined influence of cognitive flexibility and response inhibition in predicting rhyme recognition suggests a synergistic relationship between the ability to adapt to changing cognitive demands and the capacity to suppress irrelevant information, both of which are essential for successful performance in tasks requiring phonetic analysis and categorization. In relation to the composite index of metaphonology, the findings indicated a significant predictive relationship between EF measures, specifically response inhibition, and metaphonology. Thus, strong executive skills, especially inhibitory control, during preschool years are crucial for the development of proficient metaphonological skills. This result is in line with previous studies reporting that inhibition appears to be the most important EF with respect to pre-literacy e.g., [43,56].

Regarding the relationship between pre-math and EF, the current study demonstrated a significant correlation between response inhibition and all pre-math subtests, except for the number name matching subtest. Simultaneously, working memory correlated with the series completion subtest. Response inhibition predicted series completion and approached significance in predicting the comparison of Arabic numbers. Response inhibition could play a critical role in these tasks by enabling children to suppress impulsive responses and carefully analyze the sequential information presented. By inhibiting premature responses and considering multiple possibilities, children with stronger response inhibition are better equipped to discern underlying patterns and accurately complete series tasks. Similarly, when comparing Arabic numbers, individuals must inhibit irrelevant information and focus on the specific numerical properties being compared. Response inhibition aids in this process by facilitating selective attention to relevant numerical features while disregarding distracting elements. Although the significance level of response inhibition in predicting this comparison task approached significance, it implies a trend suggesting that individuals with better response inhibition may demonstrate more accurate and efficient numerical comparison abilities. Lastly, results revealed a notable association between EF measures and pre-math, suggesting that the development of robust pre-math skills during preschool years is contingent upon the strength of executive abilities. The findings of this study align with Simanowski and Krajewski's [69] study on preschool children. Inhibition enables the learning of the concept of numbers, the relationships between them, and the ability to manipulate them as

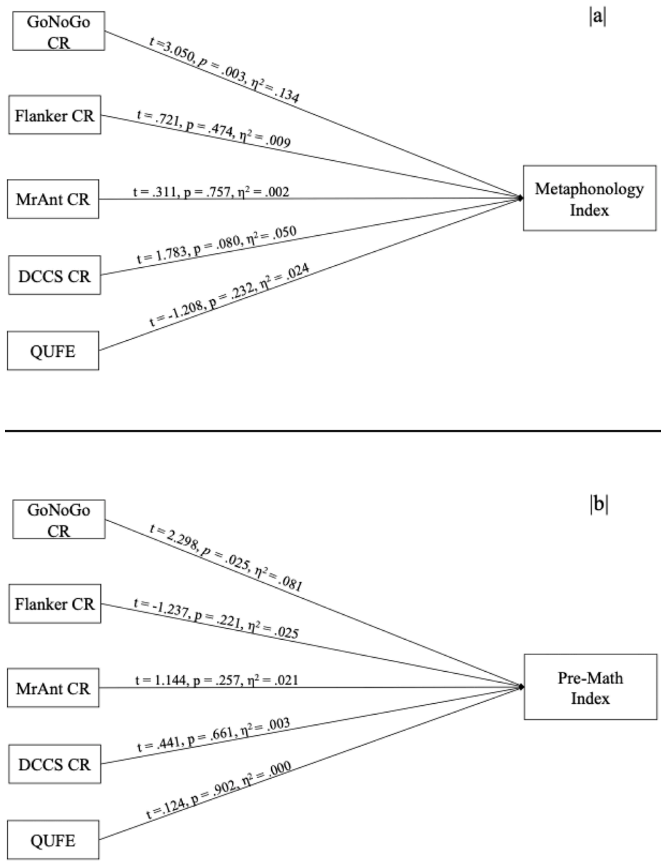

Fig. 3. Regression models with EF measures as predictors and metaphonology and pre-math as outcome measure.
For each predictor, t value, p value and effect size (small $\geq$ 0.01, medium $\geq$ 0.06, large $\geq$ 0.14) are indicated.

desired. Altogether, this result could be interpreted as a suggestion that the ability to control or suppress automatic responses may play a key role in the development of mathematical competence during childhood.

At the same time, the role of working memory approaching significance in predicting series completion should be discussed. In the context of series completion tasks, children must maintain and manipulate information about the sequence of items in their working memory while identifying underlying patterns and completing the series. The proximity to significance implies that there may be a trend indicating that individuals with better working memory performance tend to exhibit greater proficiency in series completion tasks. However, the statistical evidence falls just short of conventional levels of significance, indicating that further research with larger sample sizes or refined measurement techniques may be needed to confirm this relationship conclusively.

It should be emphasized that the role of executive behavior, as assessed by the parents, was not significant. Although it is recognized that executive functions can play a role both in indirectly promoting appropriate behavior for academic learning and directly in specific literacy and math skills, this result suggests a primary direct effect of basic EF. This result may suggest that learning prerequisites are usually acquired outside of a structured formal setting, thus being less affected by the behavioral self-regulation that is more needed in the primary school context. Nevertheless, it must be acknowledged that in the present study, only a full composite score was computed whereas looking at the sub-scores individually could reveal different effects of different dimensions of EF behavior as assessed by indirect measures.

A final comment on the central role of inhibition in relation to the other components could refer to the fact that inhibition, unlike working memory and cognitive flexibility, is the first component to emerge [4], thus playing a major role in the preschool age. Overall, the predictive association between response inhibition and tasks involving analytical requests underscores the importance of inhibitory control in cognitive processes requiring careful analysis, pattern recognition, and selective attention to relevant information. This suggests that children with stronger response inhibition may exhibit enhanced performance in tasks demanding these cognitive skills.

In sum, the results of this study demonstrate how crucial EF, especially response inhibition, are for the development of learning prerequisites in children during the last year of preschool.

There are several practical implications of this study. Firstly, although the present study cannot ascribe a causal role on learning acquisition to early EF, it suggests the need for studying the efficacy of interventions addressing early EF in order to support the acquisition of learning prerequisites and skills. Indeed, the findings suggest that educational programs and interventions could consider incorporating activities or strategies that specifically target the enhancement of basic EF in children. This could involve developing curricula that focus on cognitive control skills e.g., [70,71]. Recent meta-analyses have highlighted the challenges in achieving far transfer effects from interventions targeting EF. While these interventions significantly enhance EF, they often struggle to generalize improvements to other domains, such as mathematics [72–74]. To address the limitation of absent far transfer effects, recent studies have suggested the implementation of integrated interventions that train EF within specific domains. For instance, given that mathematics involves the integration of both specific math skills and EF [75], an integrated approach may be more effective in enhancing mathematical abilities compared to interventions focused solely on EF [76–78]. For instance, games that require children to solve math puzzles or engage in math-based challenges could improve their ability to focus, shift strategies, and remember numerical information. At the same time, activities that combine phonological awareness exercises (such as rhyming, segmentation) with tasks that require EF (such as sorting words by initial sounds or playing memory games with phonological elements) can enhance both sets of skills. However, as the present study did not test the efficacy of an intervention, nor did it take into account the aforementioned activities nor took into account the mentioned activities, further studies are needed in order to compare the efficacy of integrated EF interventions with traditional training on learning prerequisite acquisition.

Additionally, when considering EF interventions for preschoolers to promote later learning skills, it is crucial to acknowledge other influencing variables, such as verbal skills, that are related to early EF and support later learning abilities, thereby impacting the outcomes of the training programs. At the same time, early identification of EF difficulties is encouraged. Thus, identifying EF challenges early on becomes crucial and both teachers and parents can work together to recognize signs of difficulties related to EF and implement interventions to support children's cognitive development. However, in order to achieve this important goal, teachers must be trained in EF and must be able to refer to professionals that deal with this topic. Indeed, although the exclusive use of questionnaires or observations is important for a more ecological assessment of the child's daily functioning, this does not allow the predictive role of executive functioning on learning prerequisites to emerge. Since teachers play a vital role in children's education, training teachers to understand and address EF in the classroom can contribute to creating a more supportive learning environment. This might involve providing them with tools and techniques to foster EF development in their students. At the same time, parents can also play a significant role in supporting the development of EF in their children. Understanding the importance of these functions, parents can engage in activities at home that promote cognitive skills and self-regulation.

4.1. *Limitations*

The present study has some limitations that are worth emphasizing.

Firstly, the sample size is not very large, so future studies could verify the results of the present study on a larger sample size. Furthermore, future studies on samples with a larger age range could allow to take into account the age effect on the predictive role of EF on learning prerequisites. In addition, other distal predictors such as language or motor skills could be taken into account, so future studies could include other components of distal learning prerequisites in addition to EF [79]. At the same time, although the present study examined metaphonology and pre-math measures most commonly used in the preschool context as indicators of learning prerequisites, it must be recognized that future studies could also consider other proximal learning prerequisites such as alphabet knowledge. Another aspect that requires attention concerns the use of remote assessments in the preschool age group. Indeed, although tele-assessment in children is promising, there are several features linked to the child (e.g., the child's familiarity with the device; the child's engagement during the activity etc.) and the setting (e.g., web connectivity, parents behavior, quietness of the room etc.) that need to be considered, especially at an early age (for a review see: [64]). Another possible limitation of this study is the use of single tasks to measure EF components. Future research should consider employing a battery of tasks to assess each EF component more comprehensively, which would enhance the robustness and applicability of the results across various contexts and measures. Additionally, it is important to acknowledge that the relationships we found in this study do not allow us to attribute a causal role of EF on learning acquisition, especially when considering subsequent learning phases. Indeed, it could be that after an initial role of EF on early learning skills, the latter affect the subsequent acquisition, and other factors could interact and underpin this relationship. Thus, further longitudinal studies investigating the interplay between EF and early learning skills in predicting later learning development are needed. A further limitation of the study is its short-term longitudinal design in that EF were not measured early but always in the last year of kindergarten. In line with this, future research could consider a wider range of pre-school ages to investigate the topic in more detail. Finally, a limitation to be emphasized is related to recruitment. Specifically, the sample is a convenience sample as schools interested in the topic and collaborating with the research team joined the project.

5. Conclusion

In conclusion, this study emphasizes the role of EF in predicting metaphonology and pre-math and thus enabling the child to be 'ready' to learn reading, writing and mathematical skills once they enter school. Specifically, inhibition, the first EF to develop, is a central component in promoting learning prerequisites. The direct practical implications therefore suggest promoting the development of executive skills in preschool age in a preventive way.

CRediT authorship contribution statement

Costanza Ruffini: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marta Berni:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Giulia Pierucci:** Investigation, Data curation. **Chiara Pecini:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Statement

The research was approved by the Ethic Committee of the University of Florence reference number

0077761 date 04/06/2020. The research was carried out following Ethical guidelines of the Italian

Association of Psychology and of the Declaration of Helsinki.

The manuscript respects the following criteria:

1) This material is the authors' own original work, which has not been previously published elsewhere.

2) The paper is not currently being considered for publication elsewhere.

3) The paper reflects the authors' own research and analysis in a truthful and complete manner.

4) The paper properly credits the meaningful contributions of co-authors and co-researchers.

5) The results are appropriately placed in the context of prior and existing research.

6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.

7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

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