Cognitive and Educational Foundations of Preschool Mathematics:

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Contents

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Executive Summary

Context

1. According to the All Party Parliamentary Group for Maths & Numeracy (2014) report *Maths and numeracy in the early years*: "How children learn about numbers and develop mathematical understanding during the preschool years is vitally important and sets them on a path towards numeracy skills and confidence in later life." Early years education therefore plays a crucial role in improving outcomes for children.
2. This sets a clear need to understand the cognitive skills that children bring to the task of numeracy in preschool and to increase practitioners' knowledge of children's maths development and confidence in their teaching strategies.

Aims

3. This project extends the existing research on foundational cognitive skills in the development of early numeracy, by examining the interplay between children's domain-general (e.g., executive functions, attention) and domain-specific skills (e.g., symbolic and non-symbolic numeracy skills), rather than studying each in isolation. The focus on the acquisition of early symbolic skills is also central, because symbolic knowledge acquisition remains poorly understood in the preschool years, and yet provides a key bridge between informal and formal maths skills.
4. The project also explores factors underpinning individual differences in the home and preschool environment and their role in preschooler's acquisition of symbolic number knowledge, a key predictor of later formal maths achievement.
5. More specifically, the current project aimed to investigate preschool cognitive and educational foundations of numerical skills, by:

a. Studying the interplay of different domain-specific (e.g., counting, symbolic number knowledge) and domain-general (e.g., attention, executive functions) cognitive skills on the development of numeracy over time in preschool,
b. Assessing the impact of informal educational opportunities in the home and preschool environment on early maths skills,
c. Enriching all stages of the project through partnership with early years educators.

Methodology

6. Two hundred and thirty one 3- and 4-year-old children contributed cross-sectional data. From this broader sample, one hundred and seventy children were followed longitudinally at two time points, 5 months apart. Children were assessed on their general cognitive skills (e.g., attention, executive functions) and early number skills (e.g., counting, number naming). Furthermore, observations of 12 preschool settings provided measures for the quality of maths environment and maths-relevant language used by practitioners per preschool. Finally, parent's questionnaires gave us more insight on the children's home environment.

Findings

7. Our hierarchical linear regression analyses of children's cognitive foundations of preschool maths highlight that executive skills are a strong predictor of numeracy skills prior to school entry. This is important, because executive skills are malleable, they are amenable to intervention and may compensate for environments that are poorer in providing children with explicit maths knowledge. Furthermore, again hierarchical linear regressions show that these relationships are bidirectional, with good early numeracy skills also predicting good executive functioning. Few studies have focused on this bidirectional relationship, and yet it is important to highlight that good early numeracy also predicts good executive skills, perhaps because operating well with numerical symbols predisposes one to deal well with executive demands (such as maintaining information in mind, inhibiting irrelevant information and focusing).

Exploratory analyses in addition to the pre-registered analyses above suggest that a number of preschool measures load on both an executive and a symbolic maths latent factor, suggesting even further interplay between these skills in the preschool years.

8. Therefore, early educational programmes that focus on both executive function (e.g., self-regulation games, taking turns, focused peer attention and monitoring) and on number specific skills (e.g., a focus on symbols) are most likely to result in improved outcomes for pre-schoolers. More broadly, we suggest a comprehensive focus on both domain-general and domain-specific skills in preschool classrooms.

9. Through our exploratory mixed methods approach, we investigated “maths talk” used in preschool classrooms and discovered areas of expertise and confidence for early years practitioners, such as teaching counting skills, coupled with the need for further professional development, such as a better understanding of how to incorporate complementary, domain-general skills (e.g., attention to number in the face of distraction; inhibition games with number themes; working memory number games) into everyday number activities.

10. Investigations of home environment contributions are still ongoing in collaboration with Liverpool Moores University, but show strong preliminary effects of parental SES and education on early numerical skills. These analyses are not as yet complete, but will appear on the project website, linking to this report.

Recommendations

11. Policy makers should consider how both general (e.g., verbal, non-verbal, executive skills) and maths-specific skills (e.g., symbols) need to be considered together in preschool children.

12. Training for early year practitioners could be adjusted to provide the means to identify strengths / weaknesses in domain-general skills as well as maths-specific skills for their key children. This approach should be developed with practitioners themselves, to facilitate buy-in and scaling.

13. Teaching materials and activities could focus on ways of incorporating domain-general skills in maths learning games, not on training the executive or maths in isolation.

14. As a whole, the project highlighted ways in which practitioners and policy makers could better leverage pre-schoolers' prior number knowledge, executive skills and the preschool environment, to enrich preschool maths:

- by providing more training for teachers on how to enhance the variety of their teaching to incorporate:
    - a broader number of maths areas (e.g., place value and volume)
    - some emphasis on how number skills could be made more challenging but result in deeper learning by considering the role of domain-general skills (e.g., attention and executive functions).
- In essence, an overarching recommendation would be to seek ways of injective executive or attentional challenges into everyday maths activities to stretch children's understanding of early maths.

Aims and Context

Existing cognitive, educational and developmental research has identified significant individual differences in maths-related ability by the age of 4 (Dowker, 2005; 2008). These differences predict later academic outcomes (Duncan et al., 2007). This has prompted considerable interest in and discussion of the role of children's general cognitive abilities and influence of environment in the early years on these more specific skills such as early maths performance.

The central aim of the project was to understand how distinct cognitive and educational factors contribute to maths learning in the preschool classroom, so that ultimately learning can be optimised. We gained insight into the role of interactions between cognitive skills and educational environment in the development of early maths, by focusing on three specific sub-projects and deliverables:

1) assessing the cognitive skills that children bring to number symbol learning, including skills that are specific to mathematics (e.g., counting, knowledge of numbers as symbols, "domain-specific" henceforth for brevity) and those that are more general (e.g., attention, executive control, "domain-general" henceforth);
2) characterising individual differences in maths-specific experience in the home and preschool educational environment, to understand how they interact with children's cognitive skills;
3) enriching all stages of our study through input from Early Years Foundation Stage "EYFS" educators.

The Numerical Foundations of Early Maths Development

The cognitive foundations of emerging mathematical skills in the preschool years are under intense debate: most existing work focuses on the role of non-symbolic "number sense" (such as subitising, the ability to instantaneously recognise the number of objects in a small group without the need to count them; or magnitude comparison, the ability to identify which of two quantities contains the largest number of token objects). Alternatively, research has focused on attentional and executive skills, often pitting them against each other. We shall return to this point of conflict, but begin by highlighting that little is currently known about preschoolers' acquisition of numerical symbols, a key predictor of later mathematics achievement. Although huge efforts have focused on number sense (Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2013; Mazzocco, Feigenson, & Halberda, 2011; Starr, Libertus, & Brannon, 2013), less is known about children's acquisition of numerical symbols, which has recently emerged as the strongest predictor of growth in arithmetic skills in both preschool (Bartelet, Vaessen, Blomert, & Ansari, 2014; Chu, vanMarle, & Geary, 2015) and primary school children (Göbel, Watson, Lervåg, & Hulme, 2014; Lyons, Price, Vaessen, Blomert, & Ansari, 2014). Knowledge of numerical symbols mediates the transition from informal to formal mathematical skills (Merkley & Ansari, 2016; Purpura, Baroody, & Lonigan, 2013), and therefore it is crucial to foster this knowledge in early childhood. Importantly, understanding numerical symbols entails not only the ability to identify symbols, but also knowing that a number refers to the number of items within a set (cardinal knowledge) and how it relates to other numbers in order (ordinal knowledge, Merkley & Ansari, 2016). Yet it remains unclear exactly how *younger* pre-schoolers learn the meaning of numerical symbols, and whether or how non-symbolic, attentional skills and their interaction play a role in this process of acquisition. Children are slow to learn the semantic meaning of the first four number words over the course of the preschool years (Wynn, 1992), but less is known for quantities larger than four, and about how this knowledge is established for Arabic numerals. As such, this project aims to provide novel insight into a range of important factors influencing early maths development and, equally, how diverse maths skills can be assessed in the early years, by including measures of mathematical skill including numeral recognition, cardinal knowledge and non-symbolic magnitude comparison as well as counting.

The Influence of Broader Non-numerical Cognitive Skills

Multiple distinct preschool cognitive skills contribute to growth in maths (Dowker, 2008). Self-regulation skills such attention and executive control (e.g., the abilities to resist distraction, to inhibit inappropriate actions, to maintain information in mind, referred for brevity henceforth as "executive functions") have been found to predict maths achievement reliably, both concurrently and longitudinally, from as early as preschool (Bull, Espy, Wiebe, Sheffield, & Nelson, 2011; Clark, Sheffield, Wiebe, & Espy, 2013) and into the primary school years (Best, Miller, & Naglieri, 2011; Bull & Scerif, 2001a). These domain-general processes cluster into executive functions (Miyake et al., 2000; Wiebe et al., 2011), and sustained and selective processes (Steele, Karmiloff-Smith, Cornish, & Scerif, 2012) that, especially in the preschool period, are highly related (Steele et al., 2012). Recent theoretical suggestions propose that domain-general skills (like executive functions) and specific cognitive skills (like number sense) interact during early symbolic acquisition (Leibovich & Ansari, 2016). Therefore, targeting both general skills, domain-specific skills and their interactions is a necessary avenue to understanding early symbolic learning. A first direction for this project is therefore focusing on the interaction between both domain-general and domain-specific contributors to maths as the majority of previous research focuses on them in isolation, or measures in detail one, but not the other skills. The current state of the science also currently debates whether either domain-general of domain-specific skills are predictors of early maths to the exclusion of each other (Gilmore et al., 2013; Keller & Libertus, 2015) or whether they both matter (Clements, Sarama, & Germeroth, 2016; Geary, 2011).

Therefore, this longitudinal study aimed to test models of bidirectional associations between domain-general and domain-specific early cognitive predictors of preschool mathematics. Furthermore, the project aimed to address shortcomings of current preschool curricula and assessments, such as the Early Years Foundation Stage (EYFS) profile: these early assessments focus on numeracy targets and on generic sustained attention goals separately, but largely ignores the role of both attentional and symbolic demands of number learning.

The Influence of the Pre-school Learning Environment and Practitioner Maths Language

In addition to the diverse cognitive skills that each child brings to the task of developing into a competent early mathematician, the child's environment also plays a role (Gunderson & Levine, 2011; Maloney, Converse, Gibbs, Levine, & Beilock, 2015; Melhuish, Phan, et al., 2008; Melhuish, Sylva, et al., 2008; Skwarchuk, Sowinski, & LeFevre, 2014). For example, parents' number talk that involves counting or labelling sets of visible objects, and large sets of objects in particular, is more predictive of children's later cardinal number knowledge than other types of number talk (Gunderson & Levine, 2011). It is therefore important to better understand how differences in informal educational exposure to maths, at home and in the preschool classroom, influence emerging maths before formal instruction begins. Parents and preschool educators vary in their spontaneous and structured activities geared towards supporting early literacy, but information on this variability in the context of informal maths education is more limited (Hillman & Williams, 2015). Growing work has focused on the home learning environment as a predictor of numeracy, including ongoing collaborative work supported by The Nuffield Foundation (Simmons et al., 2019). (https://www.ljmu.ac.uk/microsites/liverpool-early-number-skills-project). Much of the existing research into the home learning environment has investigated the relation between child-directed maths language and early maths understanding, studying the quality and quantity of mathematical input from parent to child (Gunderson & Levine, 2011). However, especially given that young children spend increasing time in childcare, it is key to investigate the impact of 'maths talk' and maths resources in this preschool learning environment. In particular, the specific role of practitioners' confidence in and breadth of maths activities in the classroom has not frequently been investigated in UK-based settings.

The project therefore also considered individual differences in the maths-specific educational environment in the preschool classroom. By bringing cognitive scientists to work in partnership with pre-primary and primary education experts, we hope that the findings of this project can inform and assess the feasibility of implementation routes for future intervention in the preschool classroom.

Methodology

Study Design and Sample

In this study, 231 3- and 4-year-old children across 13 settings were recruited to a cross-sectional sample to allow us to investigate age-related differences across the preschool years. 170 of these children were tested again at a second time point, on average 5 months apart from the first time point, to provide information on change in cognitive skills.

Sample

The Children

We received signed parental consent forms for 231 children (120 boys; 111 girls) between the ages of 3 (*N* = 137) and 4 (*N* = 91) years[1], comprising our wider cross-sectional sample. 172 children were in the year preceding entry into Reception (all of whom were approached for longitudinal follow-up) and the remaining 59 children were in their penultimate year of pre-school. 170 children were successfully followed up, of which 155 were in the year preceding entry into Reception and 15 in their penultimate year of preschool. The 17 children who were in the year prior to Reception (9%) and were not successfully followed-up had either left the setting after initial testing (2), did not want to complete the tasks at the second time point and/or had incomplete data (4), the setting withdrew from the study (1 setting, 7 children) and so were not included in the longitudinal sample for analysis. Although the year group of particular interest for longitudinal follow-up were those in the year preceding Reception, 15 younger children were able to understand and willing complete the tasks at two time points and were therefore included in our longitudinal sample to maximise statistical power.

[1] Precise date of birth could not be traced for 4 children

As part of the parent questionnaire developed in collaboration with Liverpool John Moore University, parents were asked to report the ethnicity of their child, which was coded according to the categories used in the 2011 UK Census. Of the 189 children for which we received this information from parents, 149 (79%) were white, 16 (8%) were of mixed/multiple ethnic heritage, 15 (8%) were Asian, 1 (1%) was Black, 1 (1%) was classified as 'other' (a category that includes any ethnicity other than white, mixed/multiple, Asian or Black)[2]. From information given by parents who responded to the parent questionnaire and information from settings if parent questionnaires were not returned, 55 children (29%) were known to speak a language in addition to English. In total, 7 children (4%) were reported by parents to have a special educational need or disability (SEND) or as having been referred for or undergoing investigations for a suspected SEND. These children with SEND were included in the sample as they were judged to be able to understand the tasks and respond appropriately during the practice items. This inclusion provides a more accurate reflection of the population of children attending mainstream preschools in the UK than excluding them.

The Parents

Parents were asked to report demographic characteristics in questionnaires distributed during the study. Of the 189 parents who returned parent questionnaire information, 159 were female. Where possible preschool settings provided post codes if parent questionnaires had not been returned. The post code deprivation decile for each household was obtained from the English indices of deprivation 2015 online open data of the United Kingdom (Department for Communities and Local Government, http://imd-by-postcode.opendatacommunities.org/). The Mean deprivation level (IMD Decile) was 7.62 (*Range* = 2-10, *SD* = 2.26), with 1 being the most deprived level and 10 being the least deprived level. Parental qualifications were coded according to the UK National Qualification Framework (https://www.gov.uk/what-different-qualification-levels-mean/list-of-qualification-levels). This scale levels qualifications from 1 (qualifications equivalent to a lower grade

[2] Seven remaining parents preferred not to report ethnicity.

GCSE, typically taken by 16-year-olds) to 8 (doctoral level qualifications). Parental highest level of education was diverse, with a mean of M = 5.75 *(Range* = 0-8, SD = 2.04)[3].

The Early Years Settings

A range of Early Years settings were contacted across the county of Oxfordshire. A total of 13 settings were initially recruited and gave consent to participate in the study, one of which withdrew before data collection was complete. We supplied information and consent sheets directly to these preschools and asked them to distribute to the parents of 3- and 4-year-old children in attendance at their setting. Of the 12 participating settings, 5 were independently run charity nurseries or preschools; 4 were work place nurseries, and 3 were school-based nurseries (see Table 1 in Appendix) (SES *Median IMD Decile* = 8).

The Practitioners

Within the 13 original settings, 67 key workers (KW) were recruited to the study and N = 51 (76%) were interviewed (100% female). The further 16 practitioners were unable to participate in the interviews due to absence on interview days, personal commitments or their setting withdrawing from the study. Informed consent was gained from the preschool settings' manager and from individual KWs. To ensure confidentiality, data was anonymised using setting identification numbers.

Procedure

During the spring term of pre-school (T1) we assessed children's cognitive and early number skills, and undertook standardised assessments of cognitive fluency and receptive vocabulary. We revisited children approximately 5 months later, in the summer term of pre-school (T2), to administer the same battery of cognitive and numerical assessments. The children who were successfully followed up form our longitudinal sample. During the summer term of preschool (T2) we also conducted observations of the preschool settings using the Early Childhood Environment Rating

[3] 53 respondents did not return parent questionnaires.

Scale – Extended Edition (ECERS-E). Specifically, the Maths and Diversity sub scales of the ECERS-E were used to assess the quality (as measured by these particular sub scales) of the 12 participating pre-school settings. Key Workers and a selection of daily activities were also observed, and maths-relevant language used by practitioners recorded during these observed sessions. Semi-structured interviews (‘Lunch and Learn’ sessions) were held with 51 of the 67 participating Key Workers across settings discussing maths specific early years training, confidence with early maths teaching and practice.

Parent Questionnaires

We supplied paper copies of the parent questionnaire to the preschool settings and asked them to distribute to the parents of participating children. Digital copies of the parent questionnaire were also sent out to parents using an online data collection tool called Qualtrics. Parents who reported their child speaking an additional language to English in the home were also asked to complete an additional language questionnaire.

Measures collected from Children

Cognitive Measures

Executive Function Skills

Go/No-Go Task: This task was taken from the Early Years Toolbox and is designed specifically for the assessment of young children’s inhibition executive function (Howard & Melhuish, 2017). We collected data on the accuracy of go (tap the fish) and no-go (don’t tap the shark) responses and for further analysis used a computed score of “impulse control” that combines these measures. This impulse control score is ‘the product of proportional “go” (to account for the strength of the prepotent response generated by the requirement to go and catch the fish quickly) and “no-go” accuracy (to index a participant’s ability to overcome this prepotent response when sharks appeared)’ (Howard & Melhuish, 2017).

Mr Ant Task: This task was taken from the Early Years Toolbox and is designed specifically for the assessment of young children's visual-spatial short-term memory (Howard & Melhuish, 2017). On each trial participants watch an array of stickers appear on Mr Ant's body (1 sticker on level 1 trials, 2 on level 2 trials etc), and after a delay they are asked to tap where the stickers were located. We collected data on the accuracy with which children could recall the arrangement/location of stickers on Mr Ant. For further analyses we used the generated points score as an index of Working Memory capacity. 'WM capacity was indexed by a point score (Morra, 1994) calculated as follows: beginning from Level 1, one point for each consecutive level in which at least two of the three trials were performed accurately, plus 1/3 of a point for all correct trials thereafter.' (Howard & Melhuish, 2017)

Animal Stroop Task: This task was based upon the classic stroop task to assess the executive function of shifting attention to task relevant stimulus dimensions, while inhibiting irrelevant ones. The task involved large and small animals and was implemented following a previously published protocol (Merkley, Thompson, & Scerif, 2016). We chose this form of the stroop task as younger children cannot read words for the traditional colour-word test. We collected data on participants' accuracy in selecting the biggest animal in real life from two pictures (both congruent and incongruent). For further analysis, we used overall accuracy.

Cancellation Task: This was a visual search task designed to assess selective attention (based on Steele et al., 2012). In this task children were asked to tap all the dogs/animals as fast as they could with a stylus pen on a Windows Surface Pro tablet. There were four runs: two exemplar runs and two category runs. The order (i.e. exemplar runs and categorical runs) was counterbalanced. For further analysis we used a computed score of quality of search (Q score) calculated by taking the square root of the number of correct responses divided by the product of the number of targets and the total time spent on the task. The measure used was the average Q score across the two category runs (following Steele et al., 2012).

Early Number Skills

Give-N Task: This is an established test of cardinal number-knowing. Data were collected on children’s ability to give the experimenter a set number of items from a larger group. Traditional reporting on the task focuses on numbers 1-5 but we also included numbers to 8 for the cross-sectional (“CS” henceforth, for brevity) data and 16 (10, 11, 14, 16) for T2 data to allow for individual differences and growth over time. For further analyses we used a score of cardinal number knowledge, computed as the maximum given numerosity counted correctly. This was defined as the highest number for which children made no errors on any trials administered.

Counting Amounts Task: This was used to assess a number of mathematic skills which are typically developing at 3-4yrs old. Participants were shown two sets of a number of objects (CS/T1 = 2,3,5,6,8; T2 = 2,3,5,6,8,10,11,14,16,18) and asked to say how many. They were instructed that they could touch or move them to count if they wanted to. The children counted both sets of objects and chose the order to complete (apples/strawberries). Participants stopped when they got two incorrect trials in a row. For further analyses we used a measure of counting accuracy, computed as the total number of correct responses across the two sets of objects (max 10 at T1 and 20 at T2).

Counting High Task: This was a rote counting task used to assess how high the participants can count correctly. For analyses we used a counting score indicating the highest number reached without error in correct verbal sequence recital.

Number Naming Task: In this digit identification task (taken from the Numeracy Screener Task) children were asked to name numbers 1-9 as they were pointed to on a page, in non-sequential order (each number appearing twice on the page). We used the total number of correctly named digits (out of 18) as a ‘digit identification’ measure for analysis.

(Non-symbolic) Magnitude Comparison Task: This task is used to assess participants' non-symbolic number system knowledge. In this game, children had to point to which quantity of two was more numerous. The ratio between the two quantities were either 0.25, 0.50 or 0.75. The trials were controlled to avoid that the more numerous quantity was perceptually the bigger quantity, with half the trials being congruent (i.e., the more numerous quantity corresponded with the visually larger quantity) and half the trials being incongruent (i.e., the more numerous quantity corresponded with the visually smaller quantity). Data were collected for analysis on overall accuracy when choosing the biggest amount as overall accuracy was shown to be the most reliable measure for magnitude comparison (Gilmore, Attridge, De Smedt, & Inglis, 2014).

Standardised Measures

BAS-3: The Picture Similarities subtest from the British Ability Scales: 3rd Edition (BAS-3 Elliott & Smith, 2011) was administered as a standardised assessment of cognitive fluency. BPVS: The British Picture Vocabulary Scale (BPVS-3) was also administered as a standardised assessment of receptive vocabulary.

These standardised assessments were administered at the start of T1 and raw scores were used as control measures of cognitive fluency and receptive vocabulary in later analysis models. Raw scores were used in the regression analysis (which included age as a control measure) in order to avoid controlling for the effect of age twice.

Educational/Environmental Measures

ECERS-E Maths Sub-Scale: the ECERS-E Maths Sub-Scale was administered to assess the process quality of maths provision at each setting. The ECERS-E was used to score each setting which could then be converted into the groupings of ‘excellent’, ‘good’, ‘poor’ and ‘inadequate’ for process quality in the curriculum area of maths.

Practitioner Maths Language Breadth: settings were observed during the spring or summer term. During the observation, practitioners were asked to deliver a normal day activity. Researchers observed for around 15 minutes at a given time period, or until the activity ended (*Mean* observation time = 14.33 minutes). Observations were carried out in all settings of a: circle time; snack or lunch; and child-led activity. In 9 of the 12 settings, an adult-led activity was also observed, but this was not universal practice across settings. Although practitioners were informed about the types of sessions observed, and the methods of observation, they were blind to the focus on maths language. The language the practitioner used which related to maths was recorded in writing by two research assistants (ethics precluded the use of audio recording equipment). Then deductive coding of the maths language observed was undertaken using the maths language categories established by Libertus and Braham (2016). As much extraneous maths related language was found after coding, a miscellaneous maths code was established. This included concepts such as comparative language (e.g. ‘bigger’) and shape (e.g. ‘triangle’).

Analysis Strategy and Key Findings

Cognitive Findings

Table 2 displays the mean, standard deviation and range for every task used in the longitudinal analyses for Time 1 and Time 2 (*N* = 170). This descriptive data show that all tasks improved from Time 1 to Time 2 and are therefore shown to be sensitive to change over time.

Table 2. Mean, standard deviation and range per task for Time 1 and Time 2 for all children tested longitudinally (*N* = 170).

Task	T1	T2
Go/no-go	51 (SD:22; range: 0-95)	64 (SD: 20; range: 0.08-100)
Mr. Ant	1.50 (SD: 0.76; range:0-3.33)	1.78 (SD: 0.77; range: 0-3.33)
Stroop task	74.82 (SD: 23.50; range: 0-100)	83.07 (SD: 20.54; range: 29.5-100)
Give N	4.93 (SD: 2.44; range: 1-8)	7.01 (SD: 4.10; range: 0-16)
Count high	16.74 (SD: 12.36; range: 0-100)	19.61 (SD: 13.63; range: 3-100)
Count objects	7.15 (SD: 2.44; range: 0-10)	9.95 (SD: 3.94; range: 2-20)
Number naming	11.52 (SD: 6.45; range: 0-18)	13.71 (SD: 5.25; range: 0-18)
Cancellation	0.61 (SD: 0.19; range: 0.20-1.19)	0.73 (SD: 0.19; range: 0.18-1.35)

Magnitude comparisons	77 (SD: 16; range: 33-100)	83 (SD: 12; range: 48-100)
BPVS standardised	102.98 (SD: 13.76; range: 72-131)	-
BAS standardised	92.43 (SD: 11.84; range: 62-141)	-

Table 3 shows the mean, standard deviation and range for every task separately for 3- and 4-year old children (N_{age3} = 137; N_{age4} = 91) tested in the complete sample tested at Time 1 (N = 231[4]). The data show that 4-year-old-children performed higher than 3-year-old-children on every task, indicating that the tasks were sensitive to age-related differences. Table 4 (see Appendix) displays the means, standard deviations and ranges per task for all 3- and 4-year-old-children (N_{age3} = 88; N_{age4} = 82) tested longitudinally at Time 1 and Time 2. This data indicates that both younger and older children improved from Time 1 to Time 2, with older children performing better than younger children.

Table 3. Mean, standard deviation and range per task separate for 3- and 4-year-olds in the cross-sectional sample.

	3-year-olds (*N* = 137)	4-year-olds (*N* = 91)[1]
Task	T1	T1
Go/no-go	43 (SD: 22; range: 88)	56.71 (SD: 21.94; range: 95)
Mr. Ant	1.25 (SD: 0.81; range: 3)	1.64 (SD: 0.75; range: 3.33)
Stroop task	66.87 (SD: 23.05; range: 80)	79.70 (SD: 22.89; range: 100)
Give N	3.94 (SD: 2.35; range: 8)	5.64 (SD: 2.29; range: 7)
Count high	13.5 (SD: 9.40; range: 49)	18.5 (SD: 13.82; range: 98)
Count objects	4.62 (SD: 2.41; range: 8)	5.82 (SD: 2.01; range: 6)

[4] Information on the age of three children were missing. These children were not included in the longitudinal analyses.

Number naming	9.80 (SD: 6.84; range: 18)	12.67 (SD: 6.07; range: 18)
Cancellation	0.56 (SD: 0.17; range: 0.89)	0.62 (SD: 0.19; range: 0.98)
Magnitude comparisons	70.29 (SD: 16.58; range: 65)	81.48 (SD: 13.58; range: 67)
BPVS raw	49.33 (SD: 17.38; range: 82)	61.40 (SD: 17.90; range: 80)
BPVS standardised	98.48 (SD: 13.56; range: 57)	105.09 (SD: 14.08; range: 61)
BAS raw	17.52 (SD: 3.77; range: 17)	17.77 (SD: 4.65; range: 18)
BAS standardised	88.49 (SD: 11.62; range: 69)	95.23 (SD: 10.65; range: 71)

Data Reduction

Confirmatory factor analyses (CFA's) allowing covariance between latent factors were carried out on the data at Time 1 and at Time 2 in order to reduce the data into factors (Executive Functions and early mathematics skills). CFA models indicated that the data best fitted three factors (Executive Functions (EF), symbolic maths skills and non-symbolic maths skills) instead of two (EF and early maths skills). Figure 1 demonstrates a diagram of the observed measures loading onto the latent factors in both the two-factor model and the three-factor model. The three-factor model (EF, symbolic maths and non-symbolic maths) provided an acceptable fit for the data at Time 1 (robust CFI[5] = 0.923; robust RMSEA[6] = 0.077) and at Time 2 (robust CFI = 0.934; robust RMSEA = 0.067) and was used for subsequent analyses.

[5] CFI = Comparative Fit Index
[6] Root Mean Square Error of Approximation

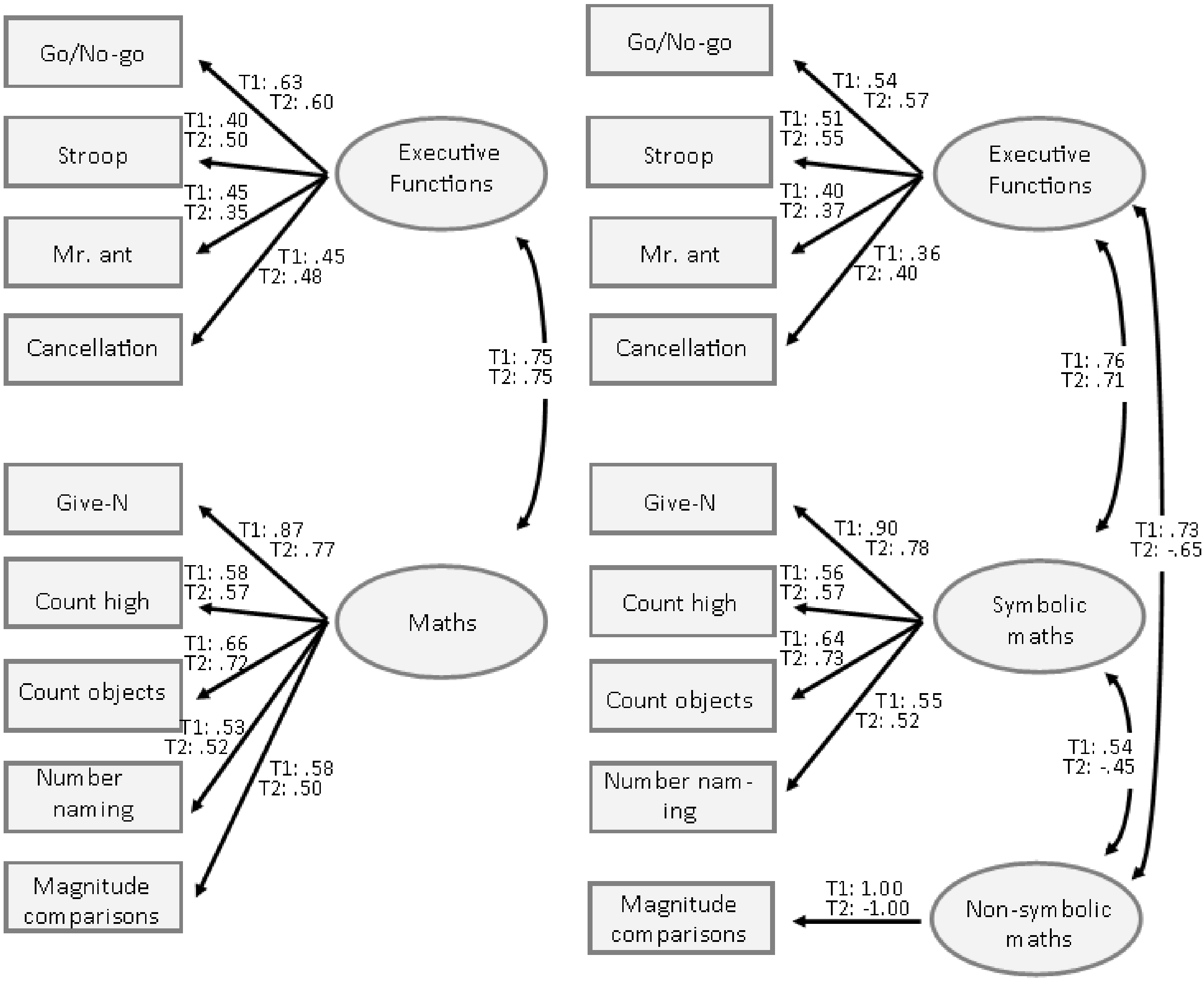

Figure 1. Diagram of observed measures and their loading on the latent factors for the two-factor model (left) and the three-factor model (right), including covariance between latent factors.

Unidirectional regression model: Executive Functions predict Symbolic Maths

Since the factor for non-symbolic maths was derived from a single observed measure, this factor was not used in this report, as the focus of this study is on latent variables. Non-symbolic skills will be investigated in depth in subsequent analyses, to be linked to this report. A hierarchical regression approach was taken to examine whether EF at Time 1 was a predictor of symbolic maths skills at Time 2 (model 1a) and whether EF at Time 1 was a predictor of growth in symbolic maths at Time 2, with symbolic maths at Time 1 as autoregressor (model 1b). By entering symbolic maths at

Time 1 as predictor (i.e., autoregressor) to symbolic maths at Time 2, we can examine whether EF predict not only symbolic maths at a later time (Time 2), but also whether EF predict the growth or improvement of symbolic maths from Time 1 to Time 2. In a hierarchical regression approach, predictors are entered stepwise, to enables us to investigate what added predictive value every step has to symbolic maths. In both models 1a and 1b, in the first step age at Time 1 was entered as sole predictor of symbolic maths at Time 2. In a second step, control measures BAS and BPVS, measured at Time 1, were entered and were significant predictors of symbolic maths at Time 2. Age, BAS and BPVS explained a total of 23.85% of the variance of the model. In step 3 in model 1a, EF at Time 1 was entered as final step and appeared as a significant predictor of symbolic maths at Time 2, improving the model to explain 50.02% of the variance. This suggests that EF are predictive of symbolic maths longitudinally, even after controlling for age, BAS and BPVS. In step 3 in model 1b, symbolic maths at Time 1 was entered as autoregressor and improved the model fit significantly, with 55.83% of the variance explained by the model with age, BAS, BPVS and symbolic maths at Time 1 as predictor of symbolic maths at Time 2. As a final step to model 1b, EF at Time 1 was entered, which significantly improved the model fit to explain 56.67% of the variance of the model. This means that EF are predictive of growth in symbolic maths, even after controlling for age, BAS and BPVS.

These results converge with previous findings suggesting that EF predicts mathematical skills (Bull & Lee, 2014; Bull & Scerif, 2001; Cragg & Gilmore, 2014; Mulder, Verhagen, Van der Ven, Slot, & Leseman, 2017; Purpura, Schmitt, & Ganley, 2017; St Clair-Thompson & Gathercole, 2006). We add to this literature by showing more specifically that EF predicts both symbolic maths and growth in symbolic maths longitudinally, even when controlling for age, BAS and BPVS (Mulder et al., 2017). This stresses the importance of EF on the development of symbolic mathematics skills in preschool children.

Bidirectional regression models

During preschool, children improve drastically in EF and symbolic maths skills simultaneously. This might suggest that there are overlapping cognitive processes developing together. Therefore, one might hypothesise that the link between EF and symbolic maths skills is bidirectional, rather than unidirectional. By using a cross-lagged regression model, the longitudinal bidirectional paths between EF and symbolic maths can be tested simultaneously (EF T1 -> symbolic maths T2 and symbolic maths T1 -> EF T2), while taking into account the covariance between EF and symbolic maths at a given time point (EF T1 – symbolic maths T1 and EF T2 – symbolic maths T2). Therefore, the latent variables EF and symbolic maths were entered in a cross-lagged regression model to examine whether EF at Time 1 predicted symbolic maths at Time 2 as well as symbolic maths at Time 1 predicting EF at Time 2 (model 2a). Age at Time 1 and the raw scores of BAS and BPVS were entered as control measures. The fit indices indicate that this model is a poor fit for the data, Robust CFI = 0.719, Robust RMSEA = 0.389. Further exploratory work also highlights that bad fit indices depend on some measures (magnitude comparison and animal stroop) cross-loading on EF and symbolic maths. To describe the link between EF and symbolic maths here, the paths between these variables will still be reported, but alternative modelling approaches are being sought, to deal better with cross-loadings. We are exploring reasons for this poor model fit and alternative more sophisticated modelling approaches, such as dynamic bifactor models, but for now suggest that the cross-lagged models should be considered with caution. In summary, EF at Time 1 significantly predicted symbolic maths at Time 2 when controlling for age, BAS and BPVS. Furthermore, symbolic maths at Time 1 also predicted EF at Time 2 when controlling for age, BAS and BPVS.

Furthermore, an autoregressive cross-lagged regression model also investigated whether EF at Time 1 predicted growth in symbolic maths at Time 2 and if symbolic maths at Time 1 predicted growth at Time 2 (model 2b). Age at Time 1 and raw scores of the BAS and BPVS were entered as control measures. This model did not fit the data well, Robust CFI = 0.874, Robust RMSEA = 0.301, but the pattern of relationships will still be reported to explore whether the link between EF and symbolic maths is bidirectional. The autoregressors EF and symbolic maths at Time 1 were significant predictors of respectively EF and symbolic maths at Time 2 when controlling for age, BAS and BPVS. EF at Time 1 predicted growth in symbolic maths at Time 2 and symbolic maths at Time 1 did not predict growth in EF at Time 2.

In order to account for the poor fit indices, unidirectional models with symbolic maths predicting EF were analysed as well, to explore whether results found in the bidirectional model can be replicated and converge on bidirectional conclusions with simpler analytical approaches. Furthermore, additional bi-directional models that are better suited for cross-loading variables are pending, and converge with the conclusions reported here. The results of the bidirectional cross-lagged model should be interpreted with caution since this model did not fit the data well. Nevertheless, the outcome from these bidirectional models converges with the results found in the unidirectional models, and with prior work on EF and mathematics achievement measures in the United States (Fuhs, Nesbitt, Farran, & Dong, 2014). EF and symbolic maths were strongly related to each other concurrently, and predict each other longitudinally, when controlling for age, BAS and BPVS. However, when modelling growth, only EF was significant as predictor of growth in symbolic maths, but symbolic maths was not predictive of growth in EF. This supports the view that that EF plays a role in the development of symbolic mathematics skills in preschool children.

Unidirectional regression model: Symbolic Maths predicts Executive Functions

Due to the poor fit indices of the bidirectional cross-lagged regression models, two additional hierarchical unidirectional regressions were conducted to further explore whether symbolic maths at Time 1 predicted EF at Time 2 (model 3a) and whether symbolic maths at Time 1 was a predictor of growth in EF at Time 2 (model 3b), with EF at Time 1 as autoregressor.

Both in model 3a and model 3b, we first entered age as predictor to EF at Time 2. In a second step, control measures BAS and BPVS (raw scores), measured at Time 1, were also entered. Raw scores of BAS and BPVS were significant predictors of EF at Time 2. The model including age, BAS and BPVS as predictors of EF at T2 explained a total of 30.58% of the variance of the model. Next, in model 3a, symbolic maths at Time 1 was entered as final step and appeared as a significant predictor of EF at Time 2, which improved the model to explain 52.77% of the variance. This confirms the results from the bidirectional model that symbolic maths predicts EF longitudinally after controlling for age, BAS and BPVS, just like EF predicts symbolic maths longitudinally. In model 3b, instead of adding symbolic maths T1 as predictor next, the autoregressor EF at T1 was entered first. EF at Time 1 as autoregressor improved the model fit significantly, with 61.72% of the variance explained by the model with age, BAS, BPVS and EF at Time 1 as predictor of EF at Time 2. As a final step to the model 3b, symbolic maths at Time 1 was entered, which did not improve the model fit. This again replicates the results found in the bidirectional model, that although symbolic maths predicts EF longitudinally, it does not predict growth in EF. Indeed, these results indicate that while symbolic maths at T1 significantly predicts EF at T2, symbolic maths at T1 does not predict growth in EF at T2 when controlling for age, BAS and BPVS. This would suggest that symbolic mathematics skills are related to EF longitudinally, but do not predict growth in EF.

In sum, these results suggest that early symbolic maths skills and EF interact with each other during preschool and play an important role as predictors of each other's outcome longitudinally. Since age, BAS and BPVS were controlled for, we suggest that these interactions are not driven by age-related differences or differences in cognitive fluency (BAS) or verbal skills (BPVS). Previous literature also found that EF were predictive of symbolic maths skills (Bull & Lee, 2014; Bull & Scerif, 2001; Cragg & Gilmore, 2014; Mulder et al., 2017; Purpura et al., 2017), however, the finding that symbolic maths skills seem predictive of EF longitudinally in preschool children is more novel, especially with regards to foundational skills, rather than maths achievement measures. Furthermore, symbolic maths skills seem not to predict growth in EF, while EF do predict growth in symbolic maths skills. This would indicate that EF have a bigger role to play in the development of symbolic maths skills than the inverse. These findings highlight the importance of EF in preschool development.

Environmental Findings: Parental Variables and Practitioner Input

Parental variables: Socio-economic status, education and language

By examining the parent questionnaires, we found that a number of environmental and educational variables play a role in early numeracy skills. For instance at the home environment level, we found that socio-economic status (SES) and availability of maths-related activities / games influence individual differences, with children from lower SES areas and from preschool settings with less availability to maths-related activities, performing on average lower on tasks overall. Since this study was designed to study the effects of settings, further research across larger setting samples is needed to unpack how these influences differ. Detailed observations focused on maths learning opportunities, specifically, have been lacking in the research literature. Using a qualitative approach, we showed that preschool classrooms vary greatly across settings in the availability of learning activities and the breadth of maths language used by practitioners with pre-schoolers. There was large disparity between language use across maths categories (See Table 5).

Out of the total 45 observed activities across 12 settings, the following proportions of activities contained language from each maths category: 82% Cardinality; 73% Counting; 60% Ordering; 49% Calculation; 47% Units of Measure; 2% Place Value; 89% Miscellaneous.[7]

Table 5: Proportion of the total 45 observed activities across 12 settings containing language from each Maths Talk category

Proportion of activities observed containing language from each Maths Talk category	Maths Talk Category
82%	Cardinality
73%	Counting
60%	Ordering
49%	Calculation
47%	Units of Measure

[7] This included concepts such as comparative language (e.g. ‘bigger’) and shape (e.g. ‘triangle’).

2%	Place Value
89%	Miscellaneous

We explored the role of further linguistic variables: pre-schoolers who receive their first exposure to number words and number learning in English may differ in their trajectories and outcomes from those who receive the same informal experience, but in languages different from their ultimate language of instruction ("emergent bilinguals"). Out of the 231 total participants, 55 are known to have EAL, 136 are known to be English monolinguals and the monolingual/EAL status of the remaining 40 are not known. Of the 33 EAL children for whom we have language questionnaires returned, 28 are bilingual and 5 are trilingual. On average monolingual children performed better than multilingual children on 7 of the 9 tasks, of which Mr Ant, Animal Stroop, Give-N, counting objects and magnitude comparisons showed a significant difference. Multilinguals outperformed monolinguals on cancellation and number naming, but these differences were not statistically significant (Table 6).

Table 6: Descriptive cognitive measures for monolingual and multi-lingual children

		GoNogo	MrAnt	AStroop	GiveN	CountHigh	CountObj	NumNam	MagCom	Canc_Q
Mono-linguals	N	122	128	134	131	129	128	129	106	129
	Mean	0.509	1.503	0.757	4.924	16.961	5.378	10.729	0.777	0.588
Multi-linguals	N	51	53	52	53	51	52	54	44	49
	Mean	0.454	1.164	0.638	4.057	13.980	4.404	11.167	0.712	0.606
Sig. diff.		--	**0.021**	**0.005**	**0.034**	--	**0.023**	--	**0.039**	--

Feedback from Early Years Practitioners about Foundational Maths Teaching

Practitioners reflected on the breadth of the maths curriculum which they felt they provided, and would like to provide, to children in the Early Years Foundation Stage ('EYFS' henceforth). A bias towards counting activities was identified by KWs who are *'…mainly focusing on counting and wonder if could focus more on other maths areas'* and *'could do more weighing as* *predominantly counting focused'.* Some settings reflected on their own progress in providing a broad mathematics curriculum: *'initially it was difficult to know what aspect of maths … but as went on got better understanding of different maths areas'* and *'we were using different language, like smaller and bigger. I wouldn't have done that previously'.*

When discussing maths confidence two areas began to emerge: the practitioner's confidence in teaching maths in the EYFS and their own confidence in maths. Statements such as *'I can do the basics; counting, simple sums'* showed that in the majority of the settings practitioners feel confident in their maths subject knowledge within the context of preschool. On the other hand, they did not feel fully confident with mathematics beyond the EYFS in multiple settings. One KW's viewpoint that they *'wouldn't have a clue in a school'* highlights the practitioners' concerns regarding their own understanding and skills with mathematical concepts.

In semi-structured interviews with EY Practitioners reflecting on their experiences of maths provision and participating in the project, many practitioners mentioned the lack of specific training for maths within both their qualifications and continuing professional development (CPD). They stated that they *'haven't had specific maths training'* and although *'a lot of people focus on counting but there doesn't seem to be enough training on how to incorporate the other areas like volume'*. This seems to be reflected in our findings on varying maths language breadth across the different areas of early maths. Of note, these practitioners' observations highlight the ongoing debate among both practitioners and policy makers on whether breadth of varied activities, as opposed to focus on fewer basic skills, would be preferable. Our data, in combination with other studies primarily originating from the United States, suggests that both depth and breadth of observed math language (and therefore practitioner training in these extended areas) may be advisable. However, replication in larger numbers of settings, controlling for all associated parental variables, is required before drawing this strong conclusion.

Discussion and Implications for Policy and Practice

The project ignited many questions at multiple levels, from further questions about the cognitive predictors of early mathematical skills, to implications for policy-makers and practitioners.

Role of EF in early maths learning/teaching

Our cognitive findings converge on prior work suggesting that EF predicts early numeracy. For the first time, and more specifically, we show that these relationships hold for foundational skills, like symbolic mathematical skills, beyond broad or coarse achievement measures. These findings suggest that we should consider these domain-general skills in the classroom environment, and ideally foster them alongside number knowledge. Of note, we show relationships that are bidirectional, with maths predicting later EF, although the predictive role of EF on maths is strongest and survives controlling for earlier maths skills. This is a very interesting and puzzling finding, although it is consistent with previous data on slightly older US pre-schoolers, for whom early maths achievement predicted later EF (Fuhs et al., 2014). How can we leverage this in practice? Good proficiency in early maths activities may predict EF because of the challenge numerical games impose, demands on maintenance in working memory and on attentional focus. Understanding these interactions might help foster better development for children who are at risk for poor numeracy or EF.

As a whole, our main cognitive findings indicate that domain-general and maths-specific cognitive skills correlate with each other and are predictive of each other longitudinally. This would suggest that domain-general and domain-specific skills do interact with each other throughout the preschool years.

Role of Preschool Provision and Practitioner Maths Language and teacher training

Observations and interviews with practitioners paint a picture of preschool maths pedagogy that focuses on counting and cardinality. This bias was identified by practitioners in their interviews and witnessed in the common use of maths language in these areas, as well as the majority of settings offering suggestions for good practice activities linked to counting and cardinality. At the other end of the spectrum, the preschool settings observed here offered children very little experience of place value and lack of examples of these activities within their settings. It would appear that there may be a mismatch between the maths categories as typically conceptualised at a research level and the real life application of practitioners, who appear to categorise maths into counting and non-counting, and have a focus on shape as well as number concepts. Many practitioners stated how they would like to receive further training on specific maths pedagogy suited for preschool. This links together with previous findings reporting that many practitioners have low qualifications, which is partly due to a lack of training opportunities provided by employers (Bonetti, 2019). Given the lack of EYFS maths training and the disparity between how the different areas of maths were discussed and observed within the settings, it may be pertinent to consider how preschool maths related professional development can be supported. Indeed, parallel work by the Nuffield Foundation suggests the need to try and facilitate professional development for early years practitioners (http://www.nuffieldfoundation.org/news/childcare-workers-face-increasing-financial-pressures-and-have-low-qualification-levels).

These observations of EYFS maths teaching and practitioner feedback on a desire for EY maths training opportunities tap into a seemingly broader misalignment between the focus of research, policy and practice with regards to early maths. Government guidelines and goals for early maths highlight key skills and understanding in areas of mathematics that ‘pupils should be enabled’ to carry out by practitioners (*Statutory framework for the early years foundation stage Setting the standards for learning, development and care for children from birth to five*, 2017). However, as has been reflected in practitioner interviews, there appears to be a lack of clarity on how best to ‘enable’ these skills in practice. Although research is often conducted namely to inform and support the development of effective teaching strategies, there remains a gap between assessments and research as conducted within formal schooling and these less prescriptive early years. By incorporating practitioner feedback into future research and intervention designs, it will hopefully be possible to move towards clearer, practical insights into effective early years provision in regard to these key foundational areas of learning such as maths and self-regulation. Future professional development may also benefit from training on self-regulation and executive skills, as our longitudinal data analyses indicate that symbolic mathematics skills would benefit from the development of both EF and early maths skills.

Implications for policy

In conclusion, the current findings suggest that revisions of the EYFS should take into consideration interactions across the broad cognitive (maths-specific, general) and educational foundations of preschool maths, with an integrated approach that incorporates child-level, practitioner-level and broader environmental considerations. A clear and specific recommendation is the suggestion of developing CPD opportunities/ materials that will support practitioners to integrate a wider range of maths activities into their practice – to add variety and more comprehensive coverage of skills - ranging from an awareness of the maths-specific skills of their key children, to how to broaden them, to attentional and executive skills that children bring to the task of learning.

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Appendix

Table 1: Preschool setting types

Type	Description	*N*
Work place nursery	A nursery business which provides year round care for children.	4 *(urban = 4)*
Independently run charity preschool	An independent preschool or nursery which is not directly under the management of a school but runs as a charity organisation. Typically these run in term-time only.	5 *(urban =1, rural = 4)*
School based Nursery	A nursery class(es) managed by a primary, infant or a foundation-stage school.	3 *(urban =3)*

Note. Rural is defined as an area with a population below 10,000 in 'Defining Rural Areas' (DEFRA)

Table 4. Mean and standard deviation per task for Time 1 and Time 2 separate for 3- and 4-year-olds

	3-year-olds (*N* = 88)		4-year-olds (*N* = 82)	
Task	T1	T2	T1	T2
Go/no-go	46 (SD: 20; range: 87)	60 (SD: 22; range: 92)	56 (SD: 22; range: 95)	69 (SD: 16; range: 72)
Mr. Ant	1.32 (SD: 0.76; range: 3)	1.70 (SD: 0.83; range: 3.33)	1.68 (SD: 0.73; range: 3.33)	1.85 (SD: 0.70; range: 3.33)
Stroop task	68.68 (SD: 24.13; range: 100)	79.55 (SD: 22.38; range: 70.5)	81.33 (SD: 21.07; range: 66.5)	86.88 (SD: 17.69; range: 58.8)

Give N	4.21 (SD: 2.46; range: 7)	6.55 (SD: 4.16; range: 16)	5.70 (SD: 2.19; range: 7)	7.50 (SD: 4.00; range: 14)
Count high	14.79 (SD: 10.15; range: 49)	17.17 (SD: 10.96; range: 57)	18.84 (SD: 14.14; range: 98)	22.22 (SD: 15.65; range: 97)
Count objects	6.55 (SD: 2.68; range: 10)	9.77 (SD: 4.22; range: 17)	7.81 (SD: 1.95; range: 7)	10.15 (SD: 3.62; range: 16)
Number naming	10.42 (SD: 6.66; range: 18)	12.93 (SD: 5.53; range: 18)	12.69 (SD: 6.04; range: 18)	14.54 (SD: 4.83; range: 18)
Cancellation	0.58 (SD: 0.17; range: 0.85)	0.70 (SD: 0.19; range: 1.17)	0.63 (SD: 0.20; range: 98.85)	0.77 (SD: 0.19; range: 89.51)
Magnitude comparisons	71 (SD: 16; range: 65)	80 (SD: 13; range: 49.5)	83 (SD: 12; range: 60)	86 (SD: 9; range: 45.5)
BPVS raw	50.65 (SD: 17.49; range: 79)	-	63.00 (SD: 16.73; range: 76)	-
BPVS stnd.	99.60 (SD: 13.75; range: 57)	-	106.49 (SD: 12.95; range: 54)	-
BAS raw	17.84 (SD: 3.70; range: 17)	-	18.07 (SD: 4.64; range: 18)	-
BAS stnd.	89.64 (SD: 11.76; range: 69)	-	95.47 (SD: 11.23; range: 71)	-