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The Role of Executive Functions in Explaining Attainment Gaps in Early Maths

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Emma Blakey, Daniel Carroll, Danielle Matthews & Lucy Cragg





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Executive Summary

This project explored the role of executive functions in explaining attainment gaps in early maths skills. Executive functions are the set of high-level cognitive skills that enable us to engage in flexible, goal-directed behaviour. Our research suggests that executive functions play a role in supporting children's maths thinking, and may also explain why we see socioeconomic attainment gaps in maths. However, cognitive interventions that train executive functions are unlikely to be an effective way to narrow the attainment gap. In order to narrow this gap, cognitive interventions targeting executive functions may need to be embedded in the teaching of the specific maths skills we wish to nurture.

Background

The socioeconomic attainment gap in mathematical skills starts early in development and widens over time. Children from socially disadvantaged backgrounds tend to arrive in school less prepared to learn, placing them at long-term academic risk. Because mathematical skills are a strong predictor of overall attainment and socioeconomic status in adulthood, it is important to identify the pathways through which inequalities arise, so that attainment gaps do not perpetuate the cycle of inequality. We aimed to do this by identifying potential explanations for this relationship, and by testing a cognitive intervention to see if it could help to narrow the attainment gap.

One potential cognitive mediator of the attainment gap is executive functions. A large body of research has found links between children's maths skills and their executive functions. Research also suggests that children from less advantaged backgrounds show poorer executive function skills than children from more advantaged backgrounds. Executive functions are domain-general cognitive skills that exert top-down control over attention and behaviour. Core executive functions in early childhood in-

clude working memory, which allows us to maintain and process information, and inhibitory control, which allows us to suppress automatic but incorrect responses. Executive functions develop slowly, but show rapid development during the preschool years. Their role in supporting the regulation of behaviour is particularly important in the transition to formal schooling, when children are required to sit still, pay attention and follow instructions.

If executive functions do contribute to early attainment gaps, it would suggest that interventions to narrow these gaps should focus on improving executive functions early in development. A common approach to improving executive functions has been through cognitive training programs which directly target specific executive functions. Research with adults and older children indicate that training which targets working memory and inhibitory control can lead to improvements on trained constructs (so-called 'near transfer') but does not lead to improvements on untrained constructs ('far transfer'.) However, research with younger children has shown more promising results, and has led to the suggestion that executive functions may be more trainable early in development, when these skills are still developing.

Project Aims

We aimed to explore (1) whether executive functions can explain socioeconomic attainment gaps in early maths skills, and (2) whether a brief cognitive intervention focusing on executive function skills could help to narrow attainment gaps.

Method

We worked with 196 3- and 4-year-old children from socially diverse areas of South Yorkshire. Children were recruited from nursery schools attached to primary schools. Of these children, 175 were randomly allocated to either an executive function training group or to an active control group. Of these 175 children, 78 were boys and 97 were girls. Children had a mean age of 4 years, with ages ranging from 39 to 54 months. We used the Index of Multiple Deprivation (IMD) as a measure of children's SES. The IMD is a precise index of socioeconomic status (SES) that measures relative neighbourhood deprivation (at a street-by-street level), provided by the UK Office for National Statistics for each of the 32,844 neighbourhoods in England. While the IMD deciles spanned the full range from 1 to 10, the scores were bimodal, with 59% of children in the lowest three deciles and 35% in the highest three deciles. Only 7% of children were in deciles 4-7. Therefore, children were categorised as low SES if they lived in deciles 1-4 (N = 108) and high SES (N = 67) if they lived in deciles 5-10. The training and control groups had comparable SES profiles.

Both groups completed computerised tasks over four sessions in a month. Sessions were run once per week. They were conducted with children individually in a quiet area of their nursery, and lasted around 20 minutes. Children in the training group completed tasks in-

volving executive functions (specifically working memory and inhibitory control). Children in the active control group completed similar tasks which lasted the same amount of time. However, these control tasks did not involve executive functions. To assess the effectiveness of the training intervention, different, non-trained measures of executive function and maths skills were taken both one week before training, and again one week after training, and then at further time points up to one year later. By using very different tasks to the ones used in the intervention, it allowed us to robustly test whether the intervention was truly improving the underlying skill, as opposed to improving children's performance due to task-specific practice. The study was pre-registered and followed gold-standard CONSORT guidelines for randomised control trials.

Key Findings

At baseline, when children were in nursery, we examined the relation between SES, executive functions, and mathematical skills. We found:

- Executive functions are positively associated with maths skills, such that children with higher executive functions have higher maths skills. The correlation between executive functions and maths is significant and moderate.
- Children from low socioeconomic backgrounds have lower maths skills compared to children from high socioeconomic backgrounds. SES has a significant medium association with mathematical skills.
- Children from low socioeconomic backgrounds have lower executive function skills compared to children from high socioeconomic backgrounds. SES has significant medium associations with inhibitory control, small associations with working memory, and no association with visual-spatial short-term memory.

- Executive functions mediate, or explain the link, between socioeconomic status and children's maths skills. In other words, differences in executive function skills are one explanation for why we see attainment gaps in early maths skills.

When we examined the results of the cognitive intervention to see whether it led to improvements on non-trained tasks one-week post-test (N = 172), three months (N = 171), six months (N = 150) and one year later (N = 147), we found:

- The executive function training intervention does not lead to improvements in children's executive functions or maths skills, either in the short-term or the long-term.

Recommendations

- ◆ Executive functions play an important role in early maths and may help to explain why we see socioeconomic attainment gaps in maths skills. This would suggest that interventions designed to narrow attainment gaps need to consider executive functions.
- ◆ Improving executive functions directly via cognitive training is not likely to be an effective way to narrow early attainment gaps.
- ◆ Researchers should focus on interventions that embed executive functions in maths or classroom activities. Alternatively, for children who may be struggling, we should aim to minimise the executive function demands within learning activities.

Introduction

The socioeconomic attainment gap in mathematical skills starts early in development (Rathbun & West, 2004; Starkey & Klein, 2008), and means that children from less advantaged backgrounds tend to arrive at school less prepared to learn, placing them at long-term academic risk (Jordan & Levine, 1999). Mathematical skills are a strong predictor of overall attainment, and they predict health, wealth and socioeconomic status (SES) in adulthood (Ritchie & Bates, 2013; Rivera-Batiz, 1992). Therefore, to ensure that early attainment gaps do not perpetuate the cycle of inequality, it is important that we understand the pathways by which SES is associated with mathematical skills early in development. By doing this, we can design and test interventions to narrow the gap. In the present study, we examined whether executive functions - key cognitive skills involved in directing attention and maintaining and processing information - explain the relation between SES and mathematical skills in preschoolers. We then test a brief executive function training intervention for narrowing the attainment gap.

The relationship between SES and mathematical ability is complex, and is likely to involve both direct and indirect pathways. SES may have *direct* pathways to mathematical skills, as children from lower-SES backgrounds may be exposed to fewer mathematical learning opportunities, numerical concepts or number talk (see Elliott & Bachman, 2018). However, attainment gaps may also be driven by *indirect* pathways, through the effect SES may have on the cognitive skills that underpin mathematical skills (Lawson & Farah, 2017). In explaining the relationship between SES and mathematical

skills, a potentially important mediator is executive functions. Executive functions are domain-general cognitive skills that exert top-down control over attention and behaviour (Diamond, 2013). Key executive functions in development include working memory, which allows us to maintain and process information; and inhibitory control, which allows us to suppress automatic but incorrect responses. Working memory and inhibitory control develop rapidly during the preschool years (Garon, Bryson & Smith, 2008) and their role in the regulation of behaviour is particularly important in the transition to formal schooling, when children are required to sit still, pay attention and follow instructions (McClelland & Cameron, 2012).

While there is growing evidence that SES correlates with executive function development, there is a notable lack of research examining whether executive functions may explain the attainment gap. Only a handful of studies have examined whether executive functions may explain SES attainment gaps in children's mathematical skills (Dilworth-Bart, 2012; Fitzpatrick, McKinnon, Blair & Willoughby, 2014; Lawson & Farah, 2017). While these studies point to a potentially important role of executive functions in mediating SES attainment gaps in mathematics, their conclusions are hampered by methodological flaws (such as relying on crude measures of SES, or using very modest samples, or focusing largely on middle-class samples). Therefore, at present, only limited conclusions can be drawn regarding the extent to which executive functions mediate mathematical attainment gaps in very diverse samples.

The aims of the present study, therefore, were to determine, first, whether differences in executive functions can explain the attainment gap in mathematical skills seen between preschoolers from diverse SES backgrounds; and second, to establish whether a brief, four-session executive function training intervention can improve both executive functions and mathematical skills in preschoolers. The training intervention was based on a previous design tested on a smaller scale that found improvements in working memory for 4-year-olds from mid-SES backgrounds (Blakey &

Carroll, 2015). In the present study, we use a rigorous randomised control study design to test the intervention with children from socially diverse backgrounds. Specifically, we compared our intervention to an active control group, in line with gold-standard randomised control trial (RCT) principles known as CONSORT guidelines; and we examined whether the intervention led to improvements in different, non-trained tasks at post-test and up to one year later, with experimenters blind to the condition allocation of the children.

Method

Participants

One hundred and seventy-five 3- to 4-year-olds were recruited from eight preschools in socio-economically diverse areas of South Yorkshire (mean age = 48 months; 78 males, 97 females). This sample size was powered to detect a small-medium one-tailed effect in favour of the intervention, with a power of .80 and allowing for 20% attrition. Inclusion criteria were that children were typically developing; that children spoke and understood English (judged by teachers); that children were due to start formal schooling the next academic year; and that children were in a nursery school attached to, or near, the primary school that they would attend in future (to facilitate follow-up testing).

To measure children's SES, the Index of Multiple Deprivation (IMD) was used (UK Office for National Statistics). Each child's SES was calculated based on their home postcode where available (71% of children), or otherwise based on their school's postcode (29% of children). The IMD is a precise index of SES that measures relative neighbourhood deprivation (at a street-by-street level), provided by the UK Office for National Statistics (English Indices of Deprivation, 2015) for each of the 32,844 neighbourhoods in England. The IMD is calculated using the following indicators of SES: employment; income; education and skills; health and disability; health provision; crime; barriers to housing and services; and the living environment. While the IMD deciles spanned the full

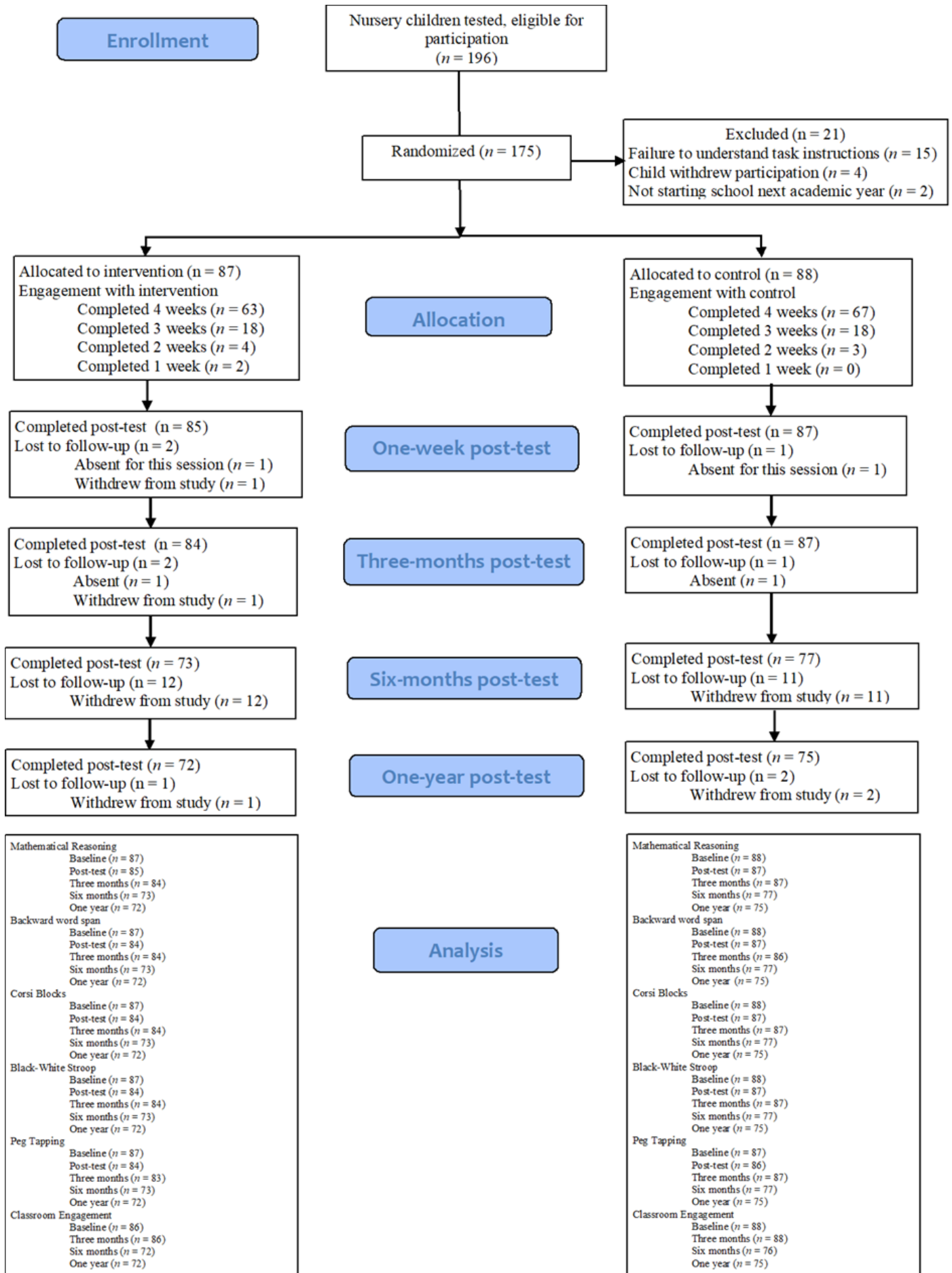


Figure 1: Flow of participants through the trial.

range from 1 to 10, the scores were bimodal, with 59% of children in the lowest three deciles and 35% in the highest three deciles. Only 7% of children were in deciles 4-7. Therefore, children were categorised as low SES if they lived in deciles 1-4 (N = 108) and high SES (N = 67) if they lived in deciles 5-10. The two groups had comparable SES profiles: in the training group, 55 children were from low-SES backgrounds and 32 children were from high-SES backgrounds. In the control group, 53 children were from low-SES backgrounds and 35 children were from high-SES backgrounds.

The study was pre-registered at clinicaltrials.gov, used an RCT pre-test post-test design following CONSORT guidelines. Children first completed baseline measures of mathematical skills, and of executive functions (specifically visual-spatial memory, verbal working memory and inhibitory control). Participants were then randomly assigned to either the executive function training group (87 children) or the active control group (88 children), with the sole constraint that children from each of the eight participating preschools were distributed equally across the two groups to avoid clustering. Children in both groups completed a series of computerised tasks lasting 20 minutes, once a week for four weeks. Children completed these tasks individually with a trained research assistant in a quiet area of their nursery. Baseline measures of executive function and mathematical skills were re-administered by experimenters, blind to the child's group, at four separate time-points: at one week post-training, three months post-training, six months post-training and one year post-training. Measures of language ability and classroom engagement were also administered.

Procedure

Children in the Training Group were given a short computerised cognitive training intervention. The training intervention was based on a prior study showing transfer to working memory in a mid-SES sample of children (Blakey & Carroll, 2015), and comprised four training tasks all administered on a touchscreen computer. Two tasks involved working memory – the Six Boxes task and the One-back task – and two tasks involved inhibitory control – interference control (the Flanker task) and response inhibition (the Go/No-Go task). The working memory tasks required children to maintain and update task-relevant information. Specifically, the Six Boxes task required children to find different items (e.g., stickers) hiding in different objects (e.g., different coloured boxes). Each object held an item and if a child found the item, the objects would be empty. The One-back task required children to watch a stream of pictures appearing on the screen (e.g., animals) and respond when they saw the same animal as the one previously (e.g., two lion pictures back-to-back). The inhibitory control tasks required children to suppress irrelevant information or task-inappropriate responses. Specifically, the Flanker task involved children seeing a row of five pictures (such as rockets) and pressing an arrow that corresponded to the direction of the middle picture. Sometimes, the middle picture faced the same direction as all of the pictures (e.g., a row of five rockets facing left); but on other times, the middle picture faced the opposite direction to the pictures flanking it (e.g., the middle rocket facing left when the ones next to it are all facing right). The Go/No-Go task required children to press the screen when a particular picture appeared but not when other pictures appeared. One version

involved children ‘catching’ fish by pressing the fish when they appeared, but refraining from pressing sharks when they appeared (as they were told that the sharks would break the fishing net.)

Children completed all four tasks in a single session, and each task lasted approximately five minutes. The tasks were child friendly, and the pictures and story for each task changed every week to maintain children’s interest. For example, in the Flanker task where the pictures had to be pointed in order to indicate whether they were facing left or right, we had versions with rockets, parrots, fish and mice. Children also received feedback on their responses (for example, in the Go/No-Go fishing task if they caught a fish they would see the fish in the net, but if they caught a shark they

would see a broken fishing net). To ensure that tasks remained optimally challenging for children – an important aspect of cognitive training programmes – the difficulty level of all tasks was adaptive to children’s performance. If children were accurate on 75% or more of trials in a particular task, the level of difficulty for that task increased in the following session.

Children in the Active Control group completed three computerised tasks that required children to make simple perceptual judgments (such as deciding whether two pictures were the same or different). The control tasks used the same stimuli and duration as the training tasks, but made minimal demands on executive functions.



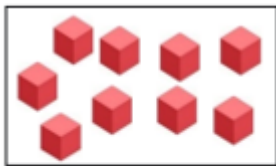
Executive function tasks used to measure working memory, visuo-spatial memory, and inhibitory control

Working Memory: The Backward Word Span



In the Backward Word Span task, children are presented with pictures of familiar objects that the experimenter reads out. Children are instructed to recall what pictures they saw, in a backwards order. If they can correctly recall all the pictures they saw in a backwards order, the number of pictures (that is, the span length) increases until children start to make mistakes. There are three trials at each span length (from 2 items to 5 items).

Visual-spatial memory: The Corsi Block Task

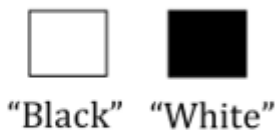


In the Corsi Block task, children see an experimenter tap out a sequence on a set of blocks set out on a tray, and must copy the sequence. If children get the sequence correct, the number of blocks tapped (that is, the span length) increases until they start to make mistakes. There are three trials at each span length (from 2 to 5 items).

Inhibitory Control:



Peg Tapping Task



Black White Stroop Task

In the Peg Tapping task, children have to tap once with a wooden peg if the experimenter taps twice, and tap twice if the experimenter taps once. There are twelve trials.

In the Black White Stroop task, children have to point to the white card if the experimenter says "black", and point to the black card if the experimenter says "white". There are twelve trials.

In order to assess training improvements to mathematical skills and executive functions, different, non-trained tasks were administered, before and after training. The executive function tasks were chosen specifically because they did not share the same surface features or instructions as training tasks, and would therefore provide a good measure of whether any improvements in performance were due to genuine improvements in executive functions, rather than simply to repeated practice on a specific task. Tasks were administered by an experimenter blind to children's condition, in the following fixed order: Backward Word Span (to measure working memory), Peg-tapping task (to measure inhibitory control), Corsi Block task (to measure visuo-spatial memory), and Black/White Stroop task (to measure inhibitory control).

To assess children's mathematics skills, the Mathematical Reasoning subtest of the Wechsler Individual Achievement Test-II battery was used (Wechsler, 2005). The Mathematical Reasoning subtest comprised 30 questions assessing the ability to identify numbers, to count, to extract information, and to solve multi-step word problems. The dependent var-

iable was the number of correct responses. This was our primary outcome measure.

To assess children's vocabulary, the Receptive Vocabulary sub-test of the Wechsler Individual Achievement Test-II battery was used (Wechsler, 2005). This comprised 16 questions assessing children's ability to match a spoken word to one of four images depicting that word. The dependent variable was the number of correct responses.

Finally, to identify any broader improvements in children's classroom behaviour, the Classroom Engagement Scale (adapted from Pagani et al., 2010) was used. A teacher blind to the child's group rated each child using the questionnaire. The questionnaire was administered at baseline, and at three months, at six months and at one year post-test. Teachers rated the extent to which children followed rules and instructions, followed directions, listened attentively, worked autonomously, worked and played cooperatively with other children, and worked neatly and carefully. The dependent variable was the sum score of the six items.



Results

Relations between SES, Executive Functions and Mathematical Skills

We first examined relations between SES, executive functions and mathematical skills at baseline when children were first tested. Table 1 shows the correlations among all measures at baseline. All executive functions tasks were positively correlated with each other, and also with mathematical skills. Table 2 shows differences in executive functions and mathematical skills between children from higher and lower SES backgrounds. Mean scores, standard deviations and an indicator of effect size is given - the standardised difference between the two mean scores of each group (Cohen's *d*).

Cohen's *d* values of .20 are considered small effects, .50 are considered medium effects and .80 are considered large effects. Consistent with previous research, SES differences in performance were only found on selective tasks that had higher executive function demands: SES had a medium effect on inhibitory control and mathematical skills, a small-to-medium effect on working memory, and very small to negligible effects on visual-spatial memory and vocabulary.

	WM	VSM	IC1	IC2	Maths	CE
Working Memory (WM)						
Visuo-Spatial Memory (VSM)	.15*					
Inhibitory Control 1 (Peg Tap)	.21**	.28***				
Inhibitory Control 2 (Stroop)	.17*	.16*	.38***			
Maths	.33***	.44***	.41***	.35***		
Class Engagement (CE)	.11	.19*	.28***	.23**	.27***	
Vocabulary	.18*	.20**	.10	.10	.20**	.15*

Note. * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 1: Pearson's correlations for all measures at baseline.

Table 2: Executive functions and mathematical skills at baseline as a function of children's SES group.

	Low SES	High SES	
	<i>M</i> (SD)	<i>M</i> (SD)	<i>d</i>
Working Memory	0.92(1.08)	1.25(1.31)	.28
Spatial Memory	3.59(1.71)	3.55(1.97)	.02
Inhibitory Control (Peg Tap)	4.86(4.90)	7.62(3.94)	.62
Inhibitory Control (Stroop)	6.97(4.43)	8.04(4.30)	.25
Mathematical Skills	6.62(2.34)	7.84(3.18)	.44
Classroom Engagement	14.66(2.48)	15.00(2.69)	.13
Vocabulary	5.77(2.30)	5.82(2.06)	.02

Do executive functions mediate the relation between SES and mathematical skills?

To investigate whether executive functions mediated the relation between SES and mathematical skills as we hypothesised, a two-stage mediation model was fitted with SES as the predictor, the latent factor executive function as the mediator, and mathematical skills as the outcome variable. Executive function tasks were combined into a single 'latent factor' which is a factor comprising the shared variance between the four executive functions tasks. One strength of latent factors is that they minimise measurement error. Before calculating this latent factor, we checked that

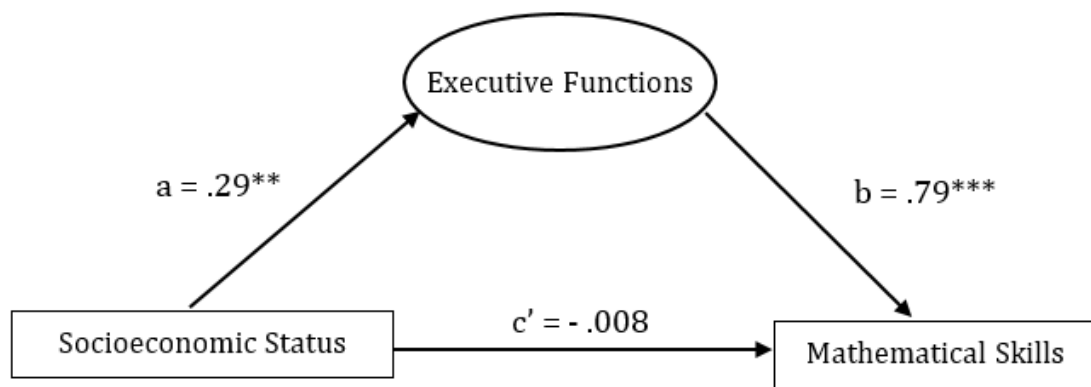
performance on the four tasks was correlated (which it was); and we also ran a confirmatory factor analysis which demonstrated that performance across the four tasks was statistically best characterised as one factor representing 'executive function' (as opposed to separate variables). To test whether executive functions mediate the relation between SES and mathematical skills, we ran mediation analyses using the bootstrapping procedure recommended by Preacher and Hayes (2008), as it has been shown to have higher power while maintaining more reasonable control over the Type I error

rate than other mediation testing procedures. Ten thousand resamples of the data were used to estimate the indirect effect (otherwise known as the mediated effect). A significant mediated effect is indicated by a point estimate of the product of coefficient that has bias-corrected 95% confidence intervals (CIs) in which the upper or lower bounds do not include zero. In the total effect model (the model without the mediator), SES had a significant, positive effect on mathematical skills ($\beta = .22$, $p = .003$) such that high SES children had significantly higher mathematical skills compared to low SES children (see Figure 2 for the mediation models). In the mediated model, SES had a significant, positive effect on executive functions ($\beta = .29$, $p = .008$), and executive functions had a significant positive effect on mathe-

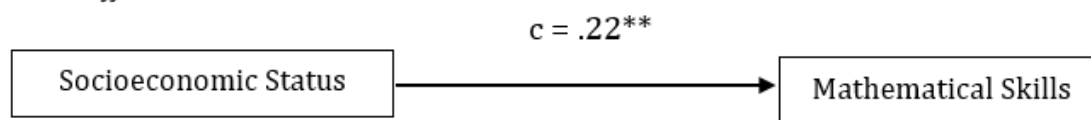
matical skills ($\beta = .79$, $p < .001$). When executive functions were controlled for in the indirect mediated model, SES had no significant effect on mathematical skills ($\beta = -.01$, $p = .934$) which suggests mediation is occurring. The results of the bootstrapping procedure to test for indirect effects revealed the indirect effect was significant, as it did not have CIs that passed through zero [95% CI: .31, 2.61] showing that executive functions mediated the relation between SES and mathematical skills. The model results remained the same when vocabulary was included as a covariate [indirect effect 95% CI: .28, 2.73].

In summary, the mediation results suggest that executive functions explain SES attainment

Mediated Model with Indirect Effect:



Total Effect Model:



Note. Asterisks indicate significant coefficients (* $p < .05$, ** $p < .01$, *** $p < .001$).

Figure 2: Mediation model showing that the relation between SES and mathematical skills is mediated by executive functions at baseline. Standardised beta weights are given.

gaps in our study. However, it is important to bear in mind that mediation models can only test mediators when they are measured variables. While the results suggest that executive functions may help to explain SES attainment gaps in maths, it does not mean they are the only explanation. Other variables we were not able to measure in our study (and so were not able to test) may also contribute towards explaining this association.

Can a brief training intervention improve children's mathematics and executive function?

The data indicated that most children did improve over the course of the training itself, particularly on the working memory tasks and the Go/No-Go measure of inhibitory control. The critical test, however, was whether the training intervention improved children's performance on different, non-trained measures of executive function, and mathematical skills. For the primary analyses, we ran ANCOVAs with group (Training vs. Active Control) as the independent variable, baseline performance as the covariate, and the relevant test of executive function or maths as the outcome variable. There were no significant effects of intervention group on children's executive function, mathematical skills or classroom engagement at post-test (all p s $> .231$), at three months (all p s $> .125$), at six months (all p s $> .205$), or at one year (all p s

$> .298$) (see Table 3 for means and standard deviations for all tasks for each time point).

As planned secondary analyses, we added a SES x Condition interaction to the model to examine whether training was more effective for high SES or low SES children. There were no significant interactions between group and SES on inhibitory control, short-term memory, mathematical skills or classroom engagement (FMAX(1,168) = 2.71, p = .101; FMIN(1,166) = .008, p = .930). There was a small but marginally significant interaction between group and SES for working memory at one year post-test, $F(1, 142) = 3.81$, p = .053, = .03. Bonferroni-adjusted pairwise comparisons showed that higher SES children in the training group had higher working memory scores than lower SES children in the training group ($M_{diff} = 1.02$, p = .006 [.30, 1.73]); that higher SES children in the training group had marginally higher working memory scores than higher SES children in the control group ($M_{diff} = .75$, p = .061 [-.04, 1.53]); but that lower SES children in the training group and lower SES children in the control group did not significantly differ ($M_{diff} = -.24$, p = .447 [-.85, .38]). This indicates that children from higher SES backgrounds in the training group may have derived some small benefit from the training intervention one year later and specifically on working memory, but that children from lower SES backgrounds did not.

Table 3: Means (and standard deviations) for each measure by group, and for the baseline, post-test, and three-month, six-month, and one-year post-test assessments.

	Executive Function Training Group					Active Control Group				
	Baseline	Post-test	3 months	6 months	One year	Baseline	Post-test	3 months	6 months	One year
Working Memory										
BWS	1.03 (1.14)	1.63 (1.30)	2.37 (1.57)	2.40 (1.55)	3.39 (1.61)	1.06 (1.23)	1.76 (1.45)	2.24 (1.69)	2.70 (1.59)	3.25 (1.46)
Corsi Block	3.69 (1.94)	3.92 (1.72)	4.11 (1.67)	4.41 (1.95)	5.64 (2.04)	3.47 (1.67)	3.91 (1.71)	4.13 (1.53)	4.45 (1.73)	5.23 (2.23)
Inhibitory Control										
Peg Tapping	6.39 (4.71)	8.13 (4.22)	9.08 (3.47)	10.21 (2.83)	11.10 (1.43)	5.43 (4.75)	8.15 (4.32)	9.17 (3.65)	10.53 (2.29)	10.88 (1.78)
BW Stroop	7.93 (4.16)	9.46 (3.16)	9.12 (3.91)	10.23 (2.73)	10.63 (2.39)	6.84 (4.59)	9.07 (3.74)	9.36 (3.17)	9.62 (3.39)	10.67 (2.27)
Academic Skills										
Maths	7.44 (2.68)	7.78 (3.37)	9.00 (3.50)	9.96 (3.50)	12.76 (3.18)	6.76 (2.80)	7.09 (3.06)	7.89 (2.98)	9.00 (3.46)	11.87 (3.27)
CE	14.92 (2.69)		15.29 (2.70)	14.74 (2.58)	15.06 (2.57)	14.67 (2.43)		15.10 (2.61)	15.16 (2.39)	15.15 (2.68)

Note. BWS = backwards word span; BW Stroop = black-white Stroop; CE = classroom engagement.

Conclusions

The aims of this study were to examine whether executive functions can *explain* SES attainment gaps in early mathematics, and to see whether training executive functions could help *narrow* attainment gaps. To do this we examined relations between executive functions and mathematical skills in a sample of preschoolers from diverse backgrounds, and ran a rigorously designed RCT over one year, to test whether an executive function training intervention would bring about cognitive improvements. We found that executive functions do explain the link between SES and mathematical skills, suggesting that one way to narrow early attainment gaps is to focus on improving these domain-general skills. However, while children showed improvement on most of the training tasks, these improvements appeared to be task-specific, rather than general: performance improvements did not transfer to different, untrained measures of executive function and mathematics.

From a theoretical perspective, our study shows that executive functions play a critical role in mathematical skills. In particular, it adds to previous work by showing that executive functions play a crucial role in the development of early, foundational mathematical skills – possibly because executive functions allow children to maintain and process numerical representations, retrieve existing conceptual knowledge and suppress irrelevant information or less useful strategies (Blair & Razza, 2007; Bull, Espy & Wiebe, 2008; Cragg & Gilmore, 2014). In the present study, performance on all of the executive function tasks correlated with mathematical skills, particularly visual-spatial memory and inhibitory control. Visual-spatial memory may help children to process

and maintain visual representations including both symbolic numbers and non-symbolic arrays, as well number lines (Kyttälä, Aunio, Lehto, Van Luit & Hautamäki, 2003). Inhibitory control has been examined less in young children, but research has shown that it predicts mathematical skills in children who have mathematical difficulties (Geary, Hoard & Bailey, 2012; Passolunghi & Pazzaglia, 2005). Inhibitory control may help children to suppress automatic but incorrect answers, or help to inhibit attention to salient, but irrelevant, distractors.

From a more applied perspective, our study crucially shows that executive functions were not merely related to children's mathematical skills, but emerged as a potential explanation for why we see SES attainment gaps in early mathematics. Lower-SES children had poorer executive functions overall than their higher-SES peers. When we examined SES differences on individual tasks, it revealed that SES differences were found only on certain tasks - specifically, ones with high executive function demands. This is important, because it shows that SES is not just affecting children's cognitive performance in general, or their ability to pay attention. It appears that executive functions are particularly vulnerable to the effects of SES. This is perhaps because executive functions' protracted development means that the factors underpinning the association with SES exert their influence for a longer period of time (Hackman, Farah & Meaney, 2010). It will be important for future research to better identify why SES is associated with executive functions. Clearly, the present study does not offer a full account of all the possible mediators of the relation between SES and mathematical skills. SES is likely to be associated with

mathematical ability via a number of more or less direct pathways. The present study suggests an important role for indirect effects via cognitive development. However, it is possible that more direct mediators play a role, such as the frequency of mathematical learning activities children engage in at home (Melhuish et al., 2008; Skwarchuk et al., 2014).

The second aim of this study was to determine if executive function training can improve both executive functions and mathematical skills in preschoolers. Against our hypothesis, we found that the intervention was not effective in improving executive functions. The fact that we did not find near transfer to untrained measures of working memory in particular was unexpected, because in a smaller-scale study with mid-SES children, this training program did lead to improvements in working memory (Blakey & Carroll, 2015). However, the lack of far transfer to mathematical skills or classroom engagement adds to a small but growing literature demonstrating that cognitive training targeting executive functions does not transfer to academic skills in children (Dunning, Holmes & Gathercole, 2013; Ang, Lee, Cheam, Poon &

Koh, 2015). In these studies, improvements tend to be found on executive function tasks that share a lot of overlap with the training tasks, but not on different executive function or academic measures.

We further hypothesised that lower-SES children would show the most benefit from the training – but again, this was not the case. We based this hypothesis on the idea of compensatory effects: that high-performing individuals (who tend to be higher SES children) would benefit less from cognitive interventions because they are performing nearer to their personal ceiling (Titz & Karbach, 2014). On the assumption that environmental effects may explain the social gradient, we hypothesised that providing extra practice in using executive functions could benefit those for whom environmental effects had not already reached ceiling. Studies have supported the idea of compensatory effects, as they have shown bigger intervention effects for low-SES children for executive function interventions (Blair & Raver, 2014), mathematical interventions (Ramani & Siegler, 2008) and other cognitive interventions (McGillion, Pine, Herbert & Mat-



thews, 2017). However, this was not borne out by our results. One possible explanation for why the intervention did not lead to improvements and why there was no interaction with SES is that (i) the training program did not improve the capacity or efficiency of executive functions within the training program, but (ii) children, particularly high-SES children, improved over training as they were able to come up with effective strategies to use (see Dunning & Holmes, 2014 for a similar suggestion in adults). This would be consistent with the lack of transfer to other tasks, as strategies tend to be very task-specific, and have little utility on tasks with different stimuli or instructions. In our study in particular, we purposefully chose non-trained tasks that did not share overlap with the training tasks as a robust test of whether training is truly improving the underlying construct.

These results suggest that executive function interventions using cognitive training are not an effective way to narrow SES attainment gaps. However, this does not mean that executive difficulties must simply be accepted and endured. While it may not be possible to improve executive function via cognitive training, the vital role executive functions play in mathematical skills may nevertheless open the door to other ways of helping children in the classroom. We propose two alternative approaches to intervention that should be tested in future research. Firstly, interventions should examine whether embedding executive function demands within the learning activities we aim to improve – such as mathematical skills – would encourage the use of helpful strategies that support executive functions. A promising example of this is the Tools of the Mind curriculum, which involves embedding executive function activities into school learning activities.

Studies have found that this programme leads to improvements in executive functions and mathematics, particularly for children from low-SES backgrounds (Blair & Raver, 2014). Secondly, it may be possible to take a reverse-engineered approach, by reducing incidental executive function demands on learning tasks, helping to scaffold children who might be struggling (see Gathercole & Alloway, 2007 for a similar approach for working memory). This could, for example, involve easing the load on working memory by reducing the number of steps that need to be performed in a sequence, breaking down complex tasks into smaller components, and using visual aids and strategies to aid the retention and retrieval of information. To support inhibitory control, children could be encouraged to slow down when learning new material, to avoid following strategies or answers that are automatic but incorrect. Advantages of these approaches are that they do not involve taking children out of the classroom, they do not require the purchase of expensive equipment, and they can be readily implemented by educators. It will be important for future studies to continue to test these approaches in diverse samples, to determine whether they are more helpful for children who have poorer executive functions to begin with.

While the training intervention was not effective in bringing about improvements, it was nevertheless a relatively brief intervention (with only four 20-minute sessions). It is possible that more intensive training could have produced a more positive effect. While we can't rule out that possibility, the training program was deliberately designed to be brief, as prior research showed that brief interventions are as effective as longer ones in children (e.g., Blakey & Carroll, 2015; Wass et al., 2011). More-

over, shorter interventions in preschool avoid taking children out of the classroom for long, an important consideration given that attendance in preschool is vital in narrowing attainment gaps (Sylva et al., 2011). It is worth noting that several meta-analyses on working memory training have suggested that the duration of training is unrelated to the extent of transfer (Karchach & Verhaeghen, 2014; Melby-Lervåg & Hulme, 2013; Sala & Gobet, 2017). Therefore, while we might speculate that more intensive training programs could be more effective overall, the current evidence base suggest that they are unlikely to help close attainment gaps.

In sum, we tested mathematical skills and executive functions in a large sample of socially diverse 3- and 4-year-olds. Executive functions mediated the relationship between SES and

mathematical skills, suggesting that executive functions may explain why we see SES attainment gaps. However, when we ran an RCT to test whether there is a causal relation between practice using executive function skills and mathematical skills, we found that training on executive function tasks did not improve performance in executive function tasks in general, or in mathematics. We conclude that executive functions play a crucial role in early mathematical skills, but it is not feasible to train executive functions via cognitive training and obtain transfer to mathematical tasks. Rather, executive function support should be embedded in the teaching of specifically those maths skills we wish to nurture.

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Further Information:

For more information about the project and the school readiness workshop we ran, please see our website: <https://www.sheffield.ac.uk/psychology/research/groups/developmental/childrenstinking> .

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**For more information about this project,
please contact**

emma.blakey@sheffield.ac.uk

d.carroll@sheffield.ac.uk



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