How do Socioeconomic Attainment Gaps in Early Mathematical Ability Arise? An Exploration into the Home Environment, Executive Functions, and Verbal Ability

Ella James-Brabham

Thesis submitted for the degree of Doctor of Philosophy (PhD)

Department of Psychology
University of Sheffield

February 2022

Abstract

The goal of this research was to explore how early socioeconomic attainment gaps arise in mathematical skills before children begin formal schooling. Previous research has shown socioeconomic disparities in mathematical ability are visible before children begin formal education, and not only persist but widen over the course of schooling. However, we do not have a good understanding of why socioeconomic disparities in early mathematical ability arise, thus limiting our ability to develop interventions to support children before socioeconomic gradients embed. The aim of the current research was to identify child-level and home-level factors that may explain socioeconomic attainment gaps, as factors at these levels may be most susceptible to change. Four factors were explored across five studies: frequency of home mathematical activities (and how parent cognitions about mathematics relate to socioeconomic status and frequency of mathematical activities), inhibitory control, working memory, and verbal ability. These factors were chosen because they (i) relate to early mathematical ability and (ii) show socioeconomic gradients. The studies found that differences in inhibitory control and verbal ability may, in part, explain how these socioeconomic differences arise. Working memory did not appear to explain socioeconomic disparities but did emerge an important factor for early mathematical ability. Frequency of home mathematical activities did not explain socioeconomic attainment gaps in mathematics. In the empirical research, frequency of home mathematical activities did not relate to mathematical ability, but when systematically reviewing the field as a whole, a small positive relation was found. Parent beliefs about the importance of mathematics may help to explain variation in the frequency that parents engage in home mathematical activities with their child. These findings provide an important first step in identifying mechanisms by which socioeconomic disparities emerge. It is vital that future research explores these factors longitudinally before interventions can be developed with the goal of narrowing socioeconomic disparities in early mathematical ability.

Acknowledgements

First and foremost, I would like to thank my supervisor, Emma Blakey. Emma, I could not have wished for a more supportive and encouraging supervisor throughout my PhD journey. It has been an absolute pleasure and privilege to work with you on our research projects. I have learnt so much from you, and I continue to greatly value your input and advice. Thank you for always nurturing my research interests and development. I am so grateful that you have always challenged me to acquire new skills and be the best researcher I can be. Your warmth, positivity, and belief in me has enabled me to achieve everything I have. I have loved every moment working with you.

I would like to thank my other supervisors, Dan Carroll, Paul Wakeling, and Francesco Sella for their continual support and valuable input in my projects. Dan, you always provide the most insightful thoughts and feedback. I have greatly enjoyed our meetings together, particularly discussing writing and cooking (mostly breadmaking). You have galvanized me to become a better writer, and for that I am incredibly grateful. Paul, I have really enjoyed working with you. I am particularly appreciative of your sociological insights and perspectives on my work. You introduced me to one of my favourite papers 'Invisible Inequality: Social Class and Childrearing in Black Families and White Families', which I have thought about often when conducting this research. Francesco, I am incredibly grateful for your statistical knowledge, and the advice and support you have provided regarding statistical analysis.

I would like to thank Dr Jo Van Herwegen for kindly sharing her data with me, and so promptly and comprehensively answering all the questions I have had. Thank you to Professor Victoria Simms for sharing Dr Abbie Cahoon's home mathematical activities questionnaire with me and allowing me to use it in my studies. I am deeply appreciative of Dr Claudia von Bastian for taking time to provide advice, guidance, and support on conducting the meta-analysis. Claudia, I always enjoy our meetings and chats.

I am extremely grateful to the students who have helped with data collection, I could not have completed this research without each of you. Jessica Williams, thank you for your assistance with the meta-analysis and helping to collect data in nurseries, it was always a joy being in nurseries with you. Thank you to Katy Harper for also helping to collect data in nurseries. Olivia King, and Libby Hines, thank you for all your assistance with the meta-analysis. I would like to express my deepest gratitude to Toni Loveridge for doing an incredible job with data collection and helping to get so many parent questionnaires returned! It has been an absolute pleasure to work with you all.

I would like to express my greatest appreciation to the schools, teachers, parents, and children who took the time to participate in this research. Each and every one of you has made this research possible, and for that I cannot be more thankful.

A special thank you to my fellow PGR students, Steph, Danielle, Ben, Meghann, Amber, and Anton. Danielle and Ben, I am so grateful to have had your encouragement and support on our shared journey from Masters to PhD. Steph, thank you for being such a fantastic friend and providing empathy and reassurance on the rollercoaster of developmental research. You were the best travel buddy for SRCD (and for the Aquarium and cheesecake!) in Baltimore. I am looking forward to our next dinner date and obligatory gin fizz.

Thank you to my friends for being incredible, always providing the best distractions, and funniest messages. A special thank you to my Fenty housemates throughout the pandemic, Beth, Ffion, and Dom. You have provided much light relief, and a lot of fun! I am particularly grateful to Dom, who has been my honorary work colleague for much of the past year. Dom, thank you for enduring the arduous technical PhD talk, and being so supportive in my final weeks of writing. You will be relieved to know the meta-analysis is finally finished.

Last but not least, I would like to thank my family for providing unconditional love and support. I could not be where I am today without you. A special thank you to my wonderful mum who has always believed I could do it even when I did not. You are a constant inspiration in all that I do. Thank you to my dad and my brother, Albie, for keeping me grounded and always making me laugh. Thank you to my nan and grandad, who have no idea what I do but, who are so proud of me. I am forever grateful to my grandma who has always provided an abundance of love and support. Grandma, you are the most attentive and compassionate person in my life. Thank you to my partner Charlie for your continual love, support, and encouragement in all that I do. Thank you for always being there for me, taking my struggles in your stride, and for being my sounding board throughout this PhD. You remind me that there is so much life outside of work.

Financial Support

This research was made possible by the support of a 1+3 PhD scholarship from the White Rose Doctoral Training Centre, Economic and Social Research Council (ESRC). The ESRC also kindly awarded me a grant enabling me to attend the British Psychological Society Conference and to extend my PhD by three months due to the impact of the COVID-19 pandemic. I am grateful to the Department of Psychology at the University of Sheffield, who generously funded vouchers and books for the parents and children who participated in the studies. In addition, I am deeply appreciative of the Sheffield Undergraduate Research Scheme and the Sheffield on Campus Placement Scheme for each funding six-week student research internships to assist with data collection in this thesis.

Declaration

I hereby declare that the work presented in this thesis is my own, except where explicitly stated. The studies presented in this thesis were designed and conducted by myself under the supervision of Dr Emma Blakey, Dr Dan Carroll, Professor Paul Wakeling, and Dr Francesco Sella. The data presented in Chapter Two of this thesis was the baseline data from a larger intervention study designed by Dr Jo Van Herwegen at University College London. The data analysis and interpretation of the findings are entirely my own work. In Chapter Four, Study Four, 32 of the participants formed part of a pilot Masters study. The aims and scope of Study Four substantially differed from those of the Masters study. Jessica Williams assisted with data collection for Chapter Two and Chapter Four. Toni Loveridge and Katy Harper assisted with data collection for Chapter Four. Olivia King and Libby Hines assisted with data extraction for Study Five. Some of the studies presented in this thesis have been previously presented in the journal articles and conference presentations detailed in the next section ‘Publications and Presentations’.

Publications and Presentations

Publications Under Review:

Chapter Four is based on a manuscript currently under revision at *Child Development:*

James-Brabham, Loveridge, T., Sella, F. Wakeling, P., Carroll, J.C., Blakey, E. How do socioeconomic attainment gaps in early mathematics arise?

Conference Presentations:

James-Brabham, E., Loveriedge, T., Wakeling, P., Sella, F., Blakey, E. (Sept 2021). How do Socioeconomic Attainment Gaps in Early Maths Ability Arise? *British Psychological Society Developmental Section conference* (Virtual Conference, UK).

James-Brabham, E., Loveridge, T., Wakeling P., Carroll, D., Blakey, E. (April 2021). Why do we see socioeconomic attainment gaps in early mathematical ability? Poster presentation at the *Society for Research in Child Development* (Virtual Conference, USA).

James-Brabham, E., Blakey, E. (April 2021). An exploration into young children's home mathematical environment during COVID-19. Poster presentation at the *Society for Research in Child Development* (Virtual Conference, USA).

James-Brabham, E., Carroll, D., Wakeling, P., Sella, F., Blakey, E. (Oct 2020). Why do we see socioeconomic differences in early mathematical ability: A role for the home environment? Poster presentation at the *Home Math Environment Conference* (Virtual Conference, USA).

James-Brabham, E., Wakeling, P., Sella, F., Blakey, E. (Sept 2019) Why do we see socioeconomic differences in early maths skills: A role for the home environment? *British Psychological Society Cognitive and Developmental Section conference* (Stoke-on-Trent, UK).

James-Brabham, E., Loveridge, T., Wakeling, P., Blakey, E. (March 2019). Why do we see Socioeconomic Attainment Gaps in Early Maths? Poster presentation at the *Society for Research in Child Development* (Baltimore, USA).

Contents

List of Figures

List of Tables

Chapter One
Socioeconomic Attainment Gaps in Early Mathematical Ability

Chapter One begins with an introduction to socioeconomic inequality. The chapter goes on to conceptualise socioeconomic status and explore socioeconomic gradients in academic attainment more broadly. The chapter subsequently narrows its focus specifically to mathematics, exploring the importance of mathematical skills for everyday life and outcomes, the implications of socioeconomic gradients in mathematics, as well as giving an overview of mathematical development in the early years. The chapter proceeds to consider mechanisms by which socioeconomic disparities in early mathematical ability could materialise, firstly considering wider home environment factors, and going onto focus more specifically on home learning activities, as well as child-level factors including executive functions and verbal ability. The chapter concludes by highlighting current research gaps and presenting the overall aims of the thesis.

1.1. The Problem of Socioeconomic Inequality

Socioeconomic inequality is associated with a multitude of unequal outcomes including education, health, and well-being (Caro et al., 2009; Kaplan et al., 2008; Pickett & Wilkinson, 2015). The United Kingdom (UK) has one of the highest levels of income inequality within Europe and the sixth highest level amongst the 35 Organisation for Economic Co-operation and Development (OECD) countries (OECD, 2019). Furthermore, social mobility has fallen among under 44s in the UK over the past decade (Social Mobility Commission, 2017). It is estimated that 30% of children in the UK are now living in relative low-income households (i.e., below 60% of median income after housing costs), with 12% of children living in low-income households with material deprivation (Department for Work and Pensions, 2019). Child poverty is predicted to increase over the coming years (Social Mobility Commission, 2020), making it paramount to identify mechanisms by which socioeconomic inequality impacts outcomes. Identifying and understanding these mechanisms will enable the development of interventions to reduce the detrimental impact of rising income inequality and decreasing social mobility within the UK.

In the UK, the relation between socioeconomic factors and educational attainment is particularly robust (Social Mobility Commission, 2017). Socioeconomic disparities in educational attainment are visible before children begin formal education, with children from lower socioeconomic status (SES) families more likely to begin school with lower levels of measured academic ability in comparison to their higher-SES peers (Sirin, 2005). The attainment gap not only persists but widens across a child's education (Caro et al., 2009). What is more, adults with low levels of educational attainment are five times more likely to live in poverty, thus demonstrating how persistent low educational attainment perpetuates the cycle of inequality across generations (Office for National Statistics, 2014). Interestingly, early mathematical ability has been identified as one of the strongest predictors of later academic attainment, closely followed by reading and attention skills (Duncan et al., 2007). Furthermore, early mathematical ability is strongly associated with employment prospects and income, which are both markers of SES (Crawford & Cribb, 2013; Department for Business Innovation & Skills, 2012). This demonstrates the importance of early mathematical ability not only for later academic attainment but also life outcomes. Therefore, the focus of this thesis is to identify specific mechanisms by which socioeconomic status influences early mathematical ability. If specific mechanisms can be identified, this will improve theories on how SES impacts academic attainment and enable the development of interventions to target these mechanisms to narrow SES disparities in mathematical ability before they embed and widen.

1.2. Conceptualising Socioeconomic Status

Socioeconomic status (SES) is a term that will be used throughout this thesis to refer to an individual's combined social and economic standing, relative to others, within society (Baker, 2014). SES is often conceptualised as a latent construct that encompasses education, income, and occupation. Each one of these constructs represents distinct resources which may support differing aspects of cognitive development (Duncan & Magnuson, 2012). Education is often used as the first marker of SES as it strongly influences both income and occupation (Baker, 2014). Parent education is related to their parenting practise (including sensitive parenting), knowledge, and psychosocial resources, for example one's own academic self-efficacy, and is thought to impact development via parent-child interactions which shape children's developmental outcomes (Guryan et al., 2008; Kalil et al., 2012; Roubinov & Boyce, 2017). Income affects the material resources available to an individual and is commonly measured at a household level. Income may be related to developmental outcomes through the addition of resources (e.g., nutritious food, learning resources, and high-quality childcare) and the omission of stressors (e.g., quality and stability of housing). Occupation is highly related to income however, additionally, it is thought to measure an individual's social standing in society and is strongly related to an individual's social networks. Therefore, occupation is thought to shape a person's values, personality, skills, and access to opportunities, all of which relate to developmental outcomes (Baker, 2014).

While considering SES as a latent construct is both comprehensive and reduces measurement error, there are also potential benefits to keeping these constructs distinct. As highlighted in the previous paragraph, these constructs are thought to influence development in distinct ways, therefore different mechanisms may be at play when thinking about how each construct influences development. Keeping these constructs as distinct rather than creating a composite variable enables us to develop a better understanding of their unique pathways to developmental outcomes (Duncan & Magnuson, 2012). It can be challenging to acquire individual SES data when conducting research, for example when asking for income data, there is often a high nonresponse rate (Shavers, 2007). Another challenge when using these measures of SES is that there are circumstances in which they are less valid; for example, where there may be cultural barriers to collecting accurate SES data using conventional measures, such as education where it can be difficult to convert education levels from different countries, or with income, where one parent may not have information about household finances (Fairley et al., 2014; Uphoff et al., 2016). Using subjective SES measures can be beneficial in situations where conventional SES measures (i.e., education, occupation, and income) are not valid (Jackman & Jackman, 1973).

An alternative to individual measures of SES is using an area-based measure of SES. The Index of Multiple Deprivation (IMD) is a neighbourhood level measure which acts as a proxy measure of individual SES (Crawford & Greaves, 2013). The IMD is a UK government composite measure of local area deprivation derived from seven domains: income, employment, education, health, crime, barriers to housing and services, and living environment. The IMD describes how deprived a small area is relatively, based on these domains from one (most deprived) to 32,844 (least deprived) (Ministry of Housing Communities and Local Government, 2019). While it is important to note that an area-based measure of SES is less sensitive than an individual measure of SES, given that lower-SES families may live in higher-SES areas or vice versa, the IMD is commonly used in research as it is very accessible with only a postcode needed to acquire the data, and it has been consistently linked with educational outcomes (Crawford & Greaves, 2013).

1.3. Socioeconomic Status and Academic Attainment

An enduring socioeconomic gradient is observed in academic attainment, with lower SES children having, on average, significantly lower educational attainment than higher-SES children (Sirin, 2005). These socioeconomic disparities in educational attainment are observed prior to the beginning of formal education, and not only persist but widen throughout school (Caro et al., 2009; DeFlorio & Beliakoff, 2015). In the UK, at the start of primary school, children from lower-SES families are, on average, 4.3 months behind their higher-SES peers, growing to 9.5 months by the end of primary school. By the end of secondary school, children from lower-SES backgrounds are, on average 19.3 months behind their peers from higher-SES backgrounds (Educational Endowment Foundation, 2017). This demonstrates how SES disparities at the beginning of formal education widen as children advance through education.

The term 'cumulative advantage' is often used to explain the widening of the socioeconomic educational attainment gap throughout school (DiPrete & Eirich, 2006). Cumulative advantage highlights that the advantages higher-SES children will receive are not stable but compound over time. Compounding advantage results in increasingly larger advantages for higher-SES children in comparison to their lower-SES peers. This makes it increasingly harder for lower-SES children to keep up or catch up with their higher-SES peers. Indeed, data from the longitudinal Millennium Cohort Study suggests that by age seven, initially high- achieving lower-SES children are overtaken by their less able but higher-SES peers (Jerrim & Vignoles, 2013). For low-SES children who do reach a 'good' level of achievement, as indexed by the UK government, at age five, more than half do not achieve five 'good' GCSEs including English and Mathematics, compared to over two-thirds of children from higher-SES families who do achieve five 'good' GCSEs including English and Mathematics (Wellings et al., 2013). These cumulative advantages continue into adulthood as five or more 'good' GCSEs including English and Mathematics predict an individual's likelihood to progress onto A-levels and higher education. This progression in education is related to both occupation, and income, which together predict social mobility. Whereas, low levels of educational attainment are a strong predictor of poverty (Department for Education, 2014b; Galobardes et al., 2006; Office for National Statistics, 2014; UCAS, 2016).

Early interventions targeted towards disadvantaged children have been found to have larger benefits than interventions that take place later on in childhood (Shonkoff & Phillips, 2000). Early interventions are particularly important because they prevent disparities from widening with time, rather than trying to intervene later once disparities have embedded. Therefore, if we are to have the best chance of narrowing attainment gaps, it is paramount that early mechanisms by which SES impacts early academic skills are identified. This will enable the development of evidence-based interventions to support children's skills before disparities embed and widen.

1.4. The Impact of Socioeconomic Gradients in Mathematical Ability on Outcomes

As already discussed, SES disparities in early academic skills are well documented (DeFlorio & Beliakoff, 2015; Larson et al., 2015; Starkey & Klein, 2008). With regards to mathematical skills in particular, SES gradients in mathematical ability are visible in children as young as three years (Blakey et al., 2020), and not only endure but widen throughout the duration of schooling (Caro et al., 2009). Notably, an analysis of six longitudinal data sets with over 36,000 children found that early mathematical skills were the strongest predictor of later academic attainment, followed by reading and attention skills (Duncan et al., 2007). This is pertinent as it highlights the predictive power of disparities in early mathematical skills for later academic attainment more broadly. The focus on identifying SES gradients in mathematical skills is a relatively recent research direction. Most research on SES gradients in academic attainment have tended to focus on understanding mechanisms that explain SES gaps in literacy skills (Skwarchuk et al., 2014). This research has been helpful in identifying mechanisms underpinning this relation, and then using these findings to develop evidence-based interventions (e.g., McGillion et al., 2017). A similar approach is now needed to understand SES gradients in early mathematical skills.

Mathematical skills are not only important for academic attainment but are vital for functioning in everyday life in financial, social, and professional contexts. Examples of this might include working with time such as working out the time you should leave your house to arrive at your destination, scaling ingredients for the number of people you are cooking for, managing medication doses, understanding health risks, and working out your take-home income and budgeting accordingly. To highlight the importance of mathematical skills for everyday life, take the example of getting to work on time which is a scenario familiar to many of us. You have to set your alarm the night before to ensure you wake up in time to get to work at 9am. You know that it takes you 40 minutes to get ready and 15 minutes to walk to the bus stop. You read the bus timetable which tells you that the bus comes at 20 past- and 20 to- the hour and you know the bus takes 30 minutes with the morning traffic. Therefore, you work backwards to calculate the time you need to wake up: arrive at the bus stop by 8:20, which means leaving your house at 8:05, and waking up at 7:25 to arrive at work on time. You arrive at the bus stop as the bus is arriving, the bus costs £1.80, you must count the coins to give the bus driver enough money and ensure you receive the correct change. This basic every day scenario displays how mathematical skills are essential for functioning in the most basic daily tasks. It also demonstrates how if a person does not have these necessary foundational mathematical skills, they may struggle with employment which will have knock-on implications for income. This also illustrates the cyclical nature of the relation between SES and mathematical skills: while we know individuals from lower-SES backgrounds are more likely to have lower mathematical skills than people from higher-SES backgrounds, childhood mathematical skills also predict SES years later in adulthood (Ritchie & Bates, 2013).

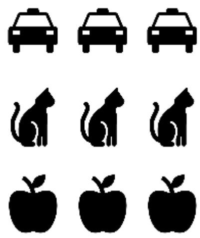
Staggeringly, in the UK it is estimated that one in four adults has a lower level of mathematical ability than is needed for everyday life (OECD, 2013). Effective mathematical interventions at age seven are estimated to result in an annual saving of £1.6 billion of government funds (Every Child a Chance Trust, 2009). This figure is perhaps less shocking when one considers that children's mathematical ability at age seven is a predictor of how long they will stay in education, as well as their future income and reporting of ill health at age 33, and their SES at 42 (Ritchie & Bates, 2013; Wagstaff et al., 2001). However, before effective interventions can be developed, we first need to identify and understand mechanisms by which SES influences early mathematical ability.

1.5. The Development of Mathematical Skills in the Early Years

'Mathematics' is an umbrella term used to refer to the study of numbers, shapes, and patterns. Non-symbolic mathematical skills are the first visible mathematical skills (Gilmore et al., 2018). Non-symbolic mathematical skills refer to one's ability to automatically know small quantities without having to count, known as subitizing, as well as being able to automatically discriminate between two quantities of dots which is the smallest and largest, known as the Approximate Number System (ANS). Infants can distinguish between small quantities (i.e., 1 vs. 2 or 2 vs. 3) (Feigenson et al., 2002). Between two to five years, the range of items children can subitize increases from one to five items (Starkey & Cooper, 1995).

In the preschool years, children begin to develop number skills which represent exact numerosities, known as symbolic number skills (Gilmore et al., 2018). Learning number words and reciting the count sequence begins to develop around age two and is the precursor to the acquisition of symbolic number skills (Wynn, 1992). When children first learn the count sequence, the meaning of number words is arbitrary; in order for number words to become numerically meaningful, children must learn to map meaning to the number words (Wynn, 1992). Gelman & Gallistel (1978) describe five principles children must acquire to understand the conceptual meaning of number words (see Table 1.1 for details and examples). Children begin by learning one-to-one correspondence, followed by the stable order principle, the abstraction principle, and the order irrelevance principle. When children acquire the final principle, the cardinal principle (i.e., knowing the last number in the count sequence represents the total quantity), they become cardinal principle knowers and are presumed to have acquired the ability to map meaning to number. Learning the cardinal principle is considered the cornerstone of developing symbolic number knowledge as this is the base that all other symbolic concepts are built upon (Cahoon, et al., 2021). Becoming a cardinal principle knower is a linear process in which children firstly learn set size one, and then two, followed by three, and set size four. Once children have become four-knowers, they soon acquire the exact meaning of higher numbers, and it is at this stage they become known as cardinal principle knowers (Wynn, 1995). The age at which children become cardinal principle knowers varies widely, ranging from three- to five- years. Notably, the age at which children become cardinal principle knowers is related to SES, with lower-SES children becoming cardinal principle knowers approximately 10 months after their higher-SES peers (Dowker, 2008; Gunderson & Levine, 2011; Sarnecka, 2021)

Table 1.1 Gelman & Gallistel's (1978) Counting Principles.

Principle	Description	Example
One-to-One Correspondence	Each object can only be counted once and receives one number word.	■ ■ ■ 'one' 'two' 'three'
Stable Order	Recite the number sequence in order.	'one', 'two', 'three', 'four', 'five', 'six'
Abstraction	Being able to count any item independent of the properties of the object.	 ■ ■ ■ 'one' 'two' 'three'
Order Irrelevance	Understanding that the order in which objects are counted is not important, as long as every object is counted.	■ ■ ■ 'five' 'one' 'four' ■ ■ ■ 'two' 'six' 'three'
Cardinal Principle	The last number in the count sequence is the total number in a set.	■ ■ ■ 'one' 'two' 'three' Total = 3

A recent longitudinal exploration of the development of number skills between ages three- to five- years identified the developmental pathway of four foundational mathematical skills: cardinal principle understanding, symbolic quantitative mapping, digit recognition, and order processing (Cahoon, et al., 2021). As discussed above, the cardinal principle is the first symbolic skill to develop. Cardinal principle acquisition is followed by the development of symbolic quantity mapping skills involving verbal number but not written digits (i.e., mapping number words to dot arrays). Next, children develop digit recognition (i.e., linking number words and quantities with Arabic digits), and finally order processing (i.e., understanding the position of a number in a sequence). While these skills have been found to develop in a consistent way (Cahoon, et al., 2021), there is evidence to suggest that the development of order processing is important for consolidating cardinal knowledge and is important for understanding the magnitude associated with numbers (Sella et al., 2020).

Following the acquisition of foundational number skills described above, children will begin to develop more advanced mathematical knowledge around symbolic arithmetic. These skills build on one another with early number knowledge predicting arithmetic ability (Östergren & Träff, 2013). Symbolic arithmetic describes the process of manipulating number (e.g., adding and subtracting). In order for children to perform operations, they must first understand the language used to describe quantities (e.g., 'largest', 'smallest'), as well as the words used for the operations themselves (e.g., adding means an increase in quantity and subtracting means a decrease in quantity). From around age four, children will begin acquiring symbolic arithmetic skills (Prather & Alibali, 2009). However, this age varies substantially based on the age at which children develop basic number skills, as these skills are essential for the development of arithmetic skills.

The Early Years Foundation Stage (EYFS) is a framework published by the UK government which sets out the knowledge and skills children in England should acquire by age five years (Department for Education, 2021b). The EYFS stipulates that by age five children should 'develop the necessary building blocks to excel mathematically' (Department for Education, 2021b). These expected building blocks are: i) 'have a deep understanding of number to 10, including the composition of each number'; ii) 'subitise (recognise quantities without counting) up to 5'; iii) 'automatically recall (without reference to rhymes, counting or other aides) number bonds up to 5 (including subtraction facts) and some number bonds to 10, including double facts'; iv) 'verbally count beyond 20, recognising the pattern of the counting system'; v) 'compare quantities up to 10 in different contexts, recognising when one quantity is greater than, less than, or the same as the other quantity'; vi) 'explore and represent patterns within numbers up to 10, including evens and odds, double facts and how quantities can be described' (Department for Education, 2021b).

Twenty percent of children do not achieve the required mathematical skills set out in the EYFS by age five (Department for Education, 2019). These children are disproportionately from lower-SES backgrounds (Department for Education, 2014a). This is particularly concerning given the cumulative nature of mathematics learning. To elaborate, children must acquire certain skills (e.g., counting), before they are able develop other skills (e.g., cardinality) which is crucial for developing advanced mathematical skills such as arithmetic (Lyons & Beilock, 2011). Therefore, becoming a later cardinal principle knower will have a knock-on effect to developing other basic mathematical skills, and also more advanced mathematical skills such as arithmetic. Consequently, it will become increasingly difficult for children who fall behind to catch up. This is supported by evidence that achieving these building blocks at age five is related to mathematical performance throughout primary school (Atkinson et al., 2022; Department for Education, 2010). Furthermore, mathematical ability at the end of primary school is a strong predictor of mathematical achievement at the end of secondary school (Benton & Sutch, 2013). This highlights that inequalities in mathematical ability embed early and these early inequalities set the path for later attainment. Therefore, if we are to decrease educational inequality, it is crucial to focus on supporting early mathematical skill development.

1.6. Identifying Mechanisms by which Socioeconomic Status Influences Early Mathematical Skills

A multitude of factors are likely to influence the socioeconomic gradient in early mathematical ability. The Ecological Systems Theory by Bronfenbrenner (1979) theorises that a child's development is influenced by a myriad of environmental factors, and that individual differences in development can be attributed to differences in the environmental factors children experience. The theory divides environmental factors into four systems which interact (see Figure 1.1). The microsystem encompasses a child's most immediate environment (e.g., home, school, and friendship groups), the mesosystem reflects the relationship between factors in the microsystem such as how home, school, and friendships interact (e.g., whether a parent plays an active role in a child's school and social life), the exosystem reflects the relationships that exist between two or more settings, one of which the child may not be directly part of, but is influenced by none the less (e.g., a workplace may affect the flexibility they have to spend time with their child), and the macrosystem contains distant people and places that effect a child which include values, beliefs, and political systems (e.g., this can affect a child's access to education and the quality of that education). The Ecological Systems Theory is a helpful framework, and commonly used to understand how environmental factors, influenced by SES, impact children's developmental outcomes (Fusarelli, 2015).

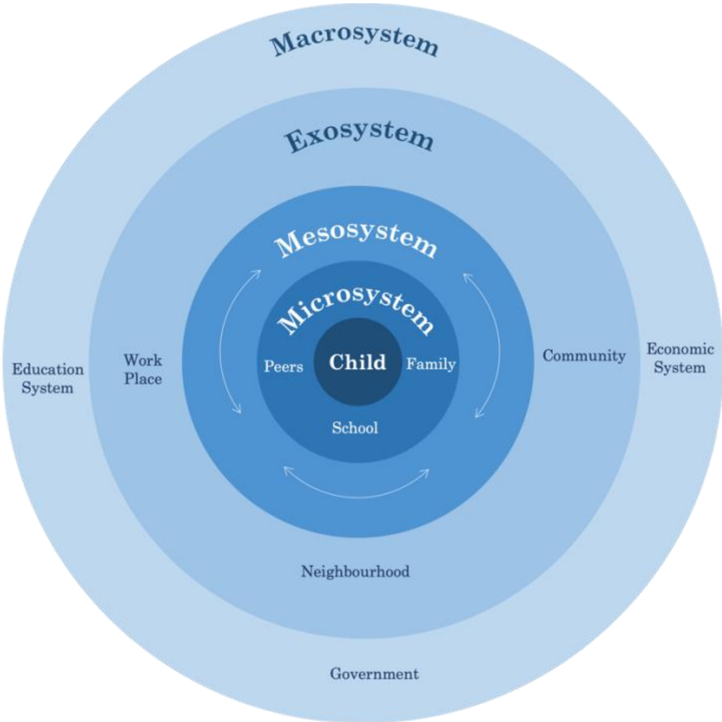


Figure 1.1 A summary of The Ecological Systems Model including specific examples of microsystem factors, mesosystem factors, exosystem factors, and macrosystem factors (Bronfenbrenner, 1979).

The Opportunity Propensity Framework (OPF) is consistent with the Ecological Systems Model (Bronfenbrenner, 1979), and builds upon it by providing a useful model by which to explore these possible factors. The OPF facilitates the exploration of mechanisms by which early life experiences shape children's outcomes by conceptually grouping variables into three factors: antecedent, opportunity, and propensity factors (Ribner et al., 2019) (see Figure 1.2). Antecedent factors represent variables which influence the context into which a child is born. *Antecedent factors* include socioeconomic variables (e.g., occupation, income, education, ethnicity), home context variables (e.g., single parent household), and the prenatal and birth context of the child (e.g., gestational age, birth weight, and lifestyle during pregnancy). *Opportunity factors* are variables which are broadly within the locus of control of the parent and school. Opportunity factors include the quality of the home environment which encompasses parenting quality, the home learning environment, and extracurricular opportunities, as well as whether the child attends nursery and the quality of nursery they attend. *Propensity factors* are child-level competencies that contribute to children's ability to benefit from early learning experiences and schooling. Propensity factors include a child's cognitive, linguistic, and motor abilities. The OPF details that antecedent, opportunity, and propensity factors are correlated with one another and relate to academic attainment (Slusser et al., 2019). Furthermore, the model postulates that there is a directional relation between each factor, in that antecedent factors explain variance in opportunity factors, which in turn explain variance in propensity factors, which have direct influence on academic attainment. Antecedent factors are structural determinants which are largely unchangeable or require large changes in policy at a global, national, or local level, such as raising families out of poverty. Whereas opportunity and propensity factors are more prone to change and thus provide opportunities for targeted interventions (Galindo & Sonnenschein, 2015). The model supports the identification of mechanisms by which SES impacts child level competencies such as cognitive function, which in turn is strongly related to academic outcomes.

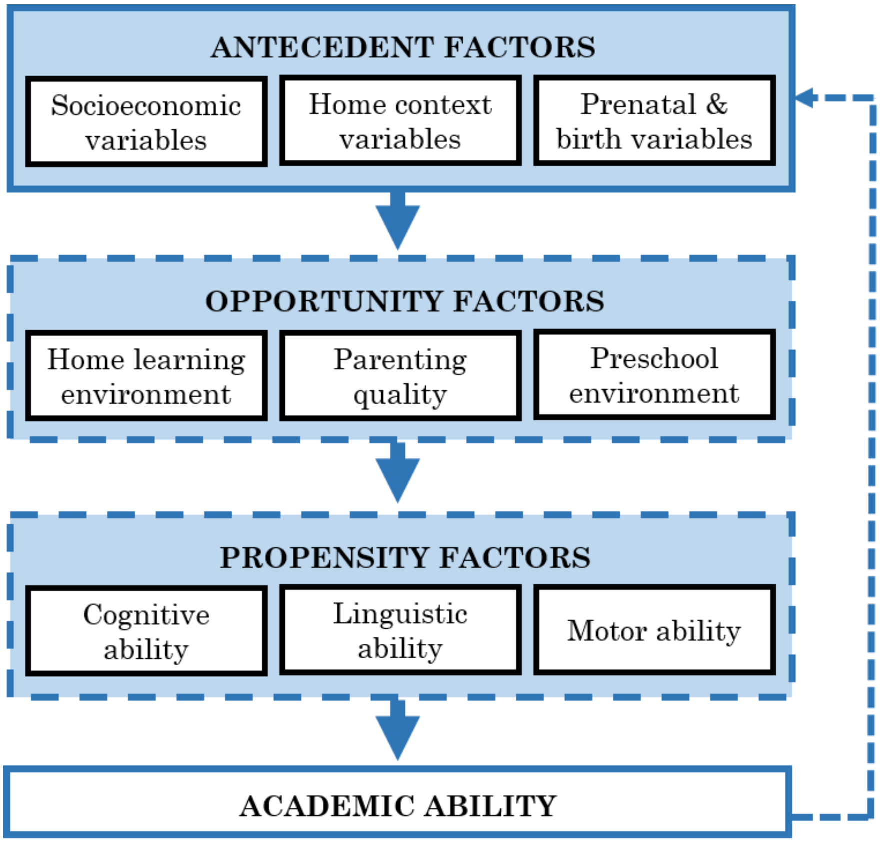


Figure 1.2 A summary of the Opportunity Propensity Framework including specific examples of antecedent factors, opportunity factors, and propensity factors (Ribner et al., 2019).

1.7. Plausible Mechanisms by which Socioeconomic Status Influences Early Mathematical Skills

There are a number of plausible antecedent, opportunity, and propensity factors that are likely to influence early mathematical ability. This thesis will focus on opportunity- and propensity- level factors given these factors are more susceptible to change than antecedent factors. Thus, if evidenced as mechanisms, they will provide a possible target for interventions. More specifically, this thesis will focus on factors which are evidenced to i) have a socioeconomic gradient, and ii) relate to early mathematical ability. Considering socioeconomic disparities in mathematical ability are seen before children begin formal education, it is likely that these disparities are routed in early experience. This literature review will now go onto give an overview of how the broader home environment may impact socioeconomic disparities in academic outcomes, and will focus specifically on three plausible mechanisms to explain SES disparities in early mathematical ability: home mathematical activities, executive functions, and verbal ability. These factors were identified because there is evidence they have SES gradients *and* relate to early mathematical ability.

1.7.1. The Influence of SES on the Home Environment

The home environment is multidimensional, made up of many factors which can influence a child's development. There are a number of home environment factors found to have an SES gradient and are related to factors associated with educational attainment. This section will give an overview of four factors which demonstrate home environment related pathways by which SES influences academic development more broadly: i) parenting styles, ii) cognitive stimulation, iii) parent-child interactions, and iv) the general home learning environment.

Firstly, parenting style is one home environment pathway by which SES may influence academic attainment. The ethnographic approach of Lareau (2002) provides valuable insight into the ways in which parenting styles may differ across families from diverse SES backgrounds; and subsequently how these differing approaches may influence the development of academic skills. Lareau (2002) conducted in-depth observations with lower-SES and middle SES families which led to the identification of two types of parenting style: 'concerted cultivation' and 'natural growth'. Parents who engaged in a 'concerted cultivation' parenting style were typically higher-SES. They enrolled their children in numerous activities, creating a structured and stimulating home environment with educational resources and a focus on language. Parents who engaged in 'concerted cultivation' parenting style tended to emphasise the importance of language and reasoning in parent-child interactions, drawing out further information from their child's questions and comments. Whereas parents who engaged in a 'natural growth' parenting style were typically lower-SES. They provided an environment conducive to their child's development (e.g., love, food, and safety) but took a less active role in structuring their child's home environment and activities. Play was typically child-led, and less emphasis was placed on the home learning environment. Instead, parents placed emphasis on deeper and richer ties with extended family. Parents would listen when children spoke, but usually did not draw out further information from their child. Lareau (2002) highlighted that there are advantages to both parenting styles, for example, the ‘natural growth’ parenting style is more likely to encourage child-led creative play, and help children learn how to structure their own time. Whereas the parenting style ‘concerted cultivation’ has been found to be more advantageous for educational attainment than natural growth (Bodovski & Farkas, 2008). This demonstrates how parenting styles may be one pathway by which SES exerts influence on academic attainment through the choices and approaches (whether implicit or explicit) parents take in setting up the home environment and interacting with their children.

Secondly, the quality of parent-child interaction has been found to vary by SES and is important for academic development. A specific type of parent-child interaction known as ‘parental scaffolding’ has been linked to cognitive development more broadly. Parental scaffolding refers to the level of support parents provide their child during a joint activity. The concept of parental scaffolding builds upon the work of Vygotsky (1978) who outlined the theory of the Zone of Proximal Development (see Figure 1.3). The Zone of Proximal Development theory stipulates that there are tasks a child can do by themselves, tasks a child can do with the support of someone who has more knowledge than the child, and tasks a child cannot do even with support. The Zone of Proximal Development is a concept referring to how development can be best supported if activities are targeted towards tasks that are beyond a child’s current level of ability but that a child can achieve with the support of a more knowledgeable other. Scaffolding refers to the specific kinds of support provided for activities within the Zone of Proximal Development to enable children to successfully complete a task. Successful scaffolding requires a parent to be sensitive to their child’s ability and needs. A parent must provide an adequate level of support to enable their child to complete the task, without providing so much support that a parent completes the task for their child, or too little support that their child is unable to complete the task (Meins, 1997; Wood et al., 1976). There is some evidence that mothers with higher levels of education provide more scaffolding for their child than mothers who have lower levels of education (Lowe et al., 2013). More recently, research has linked parental scaffolding to supporting specific areas of cognitive development, including the development of executive functions and vocabulary which are strongly related to later academic outcomes (Best et al., 2011; Blankson et al., 2015; Devine et al., 2016; Hammond et al., 2012; Hughes & Ensor, 2009; von Stumm et al., 2020).

Figure 1.3 Details The Zone of Proximal Development (Vygotsky, 1978).

Thirdly, cognitive stimulation in the home is influenced by SES and has been found to be important for academic development (Crosnoe et al., 2010; Hackman et al., 2014). Cognitive stimulation is a broad term which refers to opportunities for play and learning, this can include how involved a caregiver is in their child's learning, as well as the provision of developmentally appropriate learning materials, and the quality and complexity of interaction in the learning environment (Lurie et al., 2021). Cognitive stimulation is hypothesised to be influenced by SES through a combination of i) unequal access to resources which facilitate cognitive stimulation, with lower-SES families not having the means to purchase the resources, and ii) parents' ability to use the resources available in a way that is conducive to their child's cognitive development, for example parents' knowledge of how to use objects in a stimulating way (Crosnoe et al., 2010). Parent reports have shown both parent education and family income positively correlate with both cognitively stimulating materials and experiences (Christensen et al., 2014; Hackman et al., 2015). This is supported by observational research which has found lower-SES children had access to fewer educational materials and enriching learning experiences than their peers from higher-SES backgrounds (Bradley & Corwyn, 2002; Crosnoe et al., 2010). Children who have more cognitively stimulating environments, on average, have higher mathematics and reading development, than children who have less cognitively stimulating environments (Crosnoe et al., 2010). Interestingly, Rosen et al. (2020) found that cognitive stimulation fully mediated the relation between SES and executive functions, and that executive functions significantly predicted SES disparities in academic ability between the ages of five and six. Therefore, it is possible that cognitive stimulation influences academic development via its influence on executive functions. Therefore, cognitive stimulation is a factor by which SES influences the home environment, and subsequently impacts academic development.

Fourthly, the home learning environment is a further way in which SES may influence academic outcomes. The home learning environment takes a more specific approach to looking at broader home stimulation. It refers both to physical items, and interactions in the home, that foster the development of specific academic skills. The home learning environment includes activities directed towards learning that are developmentally appropriate, the kinds of activities parents choose to do, how they do them, and how frequently they do them. A SES gradient in the home learning environment is evident for children as young as seven months and continues into formal education (Linberg et al., 2020; Melhuish et al., 2008). Melhuish et al. (2008) assessed the home learning environment through semi-structured interviews, asking parents about the learning activities they engaged in with their three-year-old child. Activities included going to the library, playing with numbers, and painting and drawing. They found that the home learning environment at age three years predicted whether children were under-achieving, average, or over-achieving in literacy and mathematics at age five. Furthermore, a child's home learning environment at age three was found to predict whether, at age seven years, they were under-achievers, average, or over-achievers in Literacy and Mathematics. This draws attention to the role of the early home learning environment for the development of children's academic abilities.

To summarise, this section has reviewed evidence on how broad home level and parental factors may relate to general academic attainment and explain socioeconomic gradients in these skills. Specifically, parenting style, quality of parent-child interactions, home stimulation, and the resources and interactions parents provide to facilitate learning show that SES influences multiple dimensions of the home environment, and that these factors influence academic outcomes by i) influencing the home learning environment and ii) influencing the development of child-level competencies. The next sections of the literature review will explore these in turn, now with a specific focus on mathematical development.

1.7.2. Home Learning Activities and Home Mathematical Activities

The home learning activities parents do with their child is one component of the home learning environment which is potentially important for supporting the development of academic skills; and could in-part contribute towards early socioeconomic attainment gaps. Home learning activities are activities which foster the development of domain specific skills, such as reading or counting. Specifically, thinking about home activities involving mathematics (home mathematical activities), the notion is that engaging children in home mathematical activities will expose children to mathematical concepts and support their developing mathematical skills. It therefore follows that children who have been exposed to more mathematical activities in the home will have a higher level of mathematical ability than those who have not. Given that SES differences in mathematical ability are visible prior to the start of formal education, the home mathematical activities parents engage in with their children is one avenue by which these early disparities could develop.

To date, a large proportion of research exploring home learning activities has focused on home literacy activities and their relation to subsequent literacy development (Lefevre, 2000). There is evidence that home literacy activities vary by SES and influence language and literacy skills (Hart & Risley, 1995; Niklas & Schneider, 2013; Phillips & Lonigan, 2009; Sénéchal & Young, 2008; van Steensel, 2006). These findings have led to successful national campaigns encouraging parents to read to their children (Save the Children, 2016). In comparison, home mathematical activities have received considerably less attention until recently (Lefevre et al., 2009; Skwarchuk et al., 2014). In addition to many research efforts focusing on literacy, even parents report doing more home literacy activities than home mathematical activities (Blevins-Knabe et al., 2000; Cannon & Ginsburg, 2008; Lefevre et al., 2009). There is evidence to suggest that this is due to parents being less aware of the importance of early mathematical learning in comparison to literacy learning (National Research Council, 2009). Indeed, parents who report home mathematical activities to be important do engage in a higher frequency of mathematical activities with their children than parents who report home mathematical activities to be less important (Sonnenschein et al., 2012). Therefore, if home mathematical activities are found to be a mechanism by which SES disparities in mathematical ability develop, interventions could be successfully developed to raise awareness of the importance of home mathematical activities, and both encourage and support parents to engage in more home mathematical activities with their child.

When looking to evidence on SES gradients in home mathematical activities, the evidence is more limited than for home literacy activities. The majority of research looking at home mathematical activities has been conducted in socioeconomically homogeneous samples, making it difficult to draw conclusions about the influence of SES on home mathematical activities. There are a handful studies which have attempted to recruit a diverse SES sample to be able to explore whether home mathematical activities are related to SES. The *range* of activities have been found to vary by SES, with higher-SES parents more likely to engage in a wider range of mathematical activities with their children (DeFlorio & Beliakoff, 2015; Stipek et al., 1992). Furthermore, higher-SES parents are more likely to embed mathematical activities into their daily routine than lower-SES parents (DeFlorio & Beliakoff, 2015; Stipek et al., 1992). The *complexity* of home mathematical activities has also been found to be influenced by SES, with higher-SES parents setting more goal structures at multiple levels of difficulty than lower-SES parents (Saxe et al., 1987).

When looking at the relation between SES and the most commonly used measure of home mathematical activities, activity *frequency*, a more inconsistent picture emerges. Saxe et al. (1987) found no significant difference in the *frequency* of home mathematical activities for middle SES and low SES families; whereas DeFlorio & Beliakoff (2015) found small differences in the *frequency* of home mathematical activities, with middle-SES families doing a higher frequency of activities than low-SES families. However, both of these studies grouped participants into binary SES categories (middle-SES and low-SES), which may be less sensitive to capturing the influence of SES on home mathematical activities than treating SES as a continuous variable. Having a continuous measure of SES would enable studies to look at how the full distribution of SES may influence home mathematical activities. More recently, Napoli et al. (2021) took this continuous approach and found socioeconomic gradients in frequency of home mathematical activities when sex and age were controlled for. Therefore, there is some evidence that in a socioeconomically diverse sample, home mathematical activities do vary by SES.

If there are socioeconomic gradients in home mathematical activities, why might this be? Parent cognitions may be a pathway by which SES influences home mathematical activities (Elliott & Bachman, 2018c). Parents who have higher levels of education, on average, view mathematics more positively and report higher enjoyment of mathematics than parents who have lower levels of education. Therefore, these parents with higher levels of education a may be more inclined to embed these activities in their daily lives (LeFevre et al., 2010). Parent beliefs about the importance of doing mathematical activities were also found to significantly predict the frequency of home mathematical activities undertaken with their children (Sonnenschein et al., 2012). Furthermore, children of parents with negative attitudes towards mathematics have lower mathematical ability than children of parents with positive attitudes towards mathematics (Soni & Kumasi, 2015). It is possible that parents who have more confidence in their own mathematical skills are more inclined to do mathematical activities in the home compared to less confident parents. Thus, it is plausible that parents' own beliefs about the importance of mathematics and their self-efficacy of mathematics may influence the frequency of mathematical activities taking place in the home.

1.7.2.1. Home Mathematical Activities and Mathematical Ability

Over the past decade, there has been growing interest in the role of home mathematical activities for the development of early mathematical skills. The vast majority of studies have looked at the relation between *frequency* of home mathematical activities and mathematical ability (Daucourt et al., 2021; Elliott & Bachman, 2018c). The premise of this being, the more frequently parents do mathematical activities with their children, the more mathematical concepts children will be exposed to, and the more opportunities children will have to practise mathematical skills. It would therefore follow that children who are exposed to a higher frequency of mathematical activities will have better mathematical ability than children who are exposed to a lower frequency of mathematical activities. Indeed, we do see substantial variation in the frequency that parents engage in mathematical activities with their children (from every day to not at all) (DeFlorio & Beliakoff, 2015; Lefevre et al., 2009). However, the findings as to whether the variation in frequency of home mathematical activities relates to children's mathematical ability are less clear. Some studies have found that frequency of mathematical activities positively correlates with mathematical ability (e.g., Lefevre et al., 2009; Skwarchuk et al., 2014), while others have found no relation (e.g., Cahoon et al., 2021; Missall et al., 2015; Zhou et al., 2006), and some studies have found a negative relation (e.g., Blevins-Knabe et al., 2000; Ciping et al., 2015). Despite this inconsistent picture, a recent meta-analysis found a small positive relation between the home mathematical environment, which included frequency of home mathematical activities, and children's mathematical ability (Daucourt et al., 2021). This suggests that the frequency of home mathematical activities may play a role in supporting the development of early mathematical skills.

There are a number of reasons that may, in part, explain why the findings on the relation between home mathematical activities and mathematical ability are so inconsistent. These include the way mathematical activities are conceptualised across studies, the different ways mathematical ability is measured, and the sample characteristics of studies. Each of these will be discussed in turn below.

Firstly, the way in which home mathematical activities are conceptualised varies across studies. Some studies look at the overall frequency of a list of activities involving mathematical activities in the home, while others divide these activities into subcategories. For example, it is common for studies to divide home mathematical activities into formal activities, otherwise known as direct activities, and informal activities, otherwise known as indirect activities (e.g., Lefevre et al., 2009; Skwarchuk et al., 2014). Formal/ direct activities refer to mathematical activities where the teaching of mathematics is targeted and intentional, for example, using number cards (Elliott & Bachman, 2018a). Whereas informal/ indirect activities refer to activities where mathematical learning may not be the direct goal of the activities but happens incidentally, such as playing a board game which involves number. Another common subcategorization of home mathematical activities is into 'basic activities' and 'advanced activities' (Elliott & Bachman, 2018a). Basic activities refers to activities which would support children's foundational mathematical knowledge, such as counting, whereas advanced mathematical activities are activities which would support more advanced mathematical skills, such as arithmetic (e.g., Sonnenschein et al., 2012). Often, studies use factor analysis to divide activities into these categories (see Andrews et al., 2021)

There are a number of problems with sub-categorisations of home mathematical activities. Firstly, the activities divided into each subcategory are not consistent across studies, for example, talking about money, has been categorised as formal in some studies and informal in others (Lefevre et al., 2009; LeFevre et al., 2010). These inconsistencies raise issues with the theoretical basis for these categories. Indeed, a recent critique of the field has highlighted that these categories often group activities together which would be hypothesised to influence different mathematical skills, for example, formal/ direct include counting activities, symbolic number activities, and shape activities which target different mathematical competencies (Andrews et al., 2021). Therefore, if categorisation of mathematical activities is important, it may make more sense to group activities by the mathematical skill they may nurture, rather than the way in which the activity is conducted. Secondly, the formal/direct vs. informal/ indirect distinction is problematic as it assumes parents who engage in an activity such as playing a board game with their child would do so not with the intention of teaching number. However, it is plausible that one parent would use the board game to intentionally teach their child about the count sequence, while another parent would play the same board game simply to entertain the child, with no mathematical learning agenda. Therefore, for one parent a mathematical board game would be an informal/ indirect activity whereas, for another parent the board game would be a formal/direct activity. Questionnaires have not directly asked parents their intention or goal behind the activity. This highlights that it is not necessarily the type of activity you do per se, but the way that the activity is carried out.

Secondly, the way in which children's mathematical skills are measured varies widely across studies. A review by Mutaf-Yıldız et al. (2020) suggests that the differing mathematical measures implemented across studies may be influencing the inconsistent findings on the relation between home mathematical activities and mathematical ability. Daucourt et al's., (2021) recent meta-analysis, found 12 studies used a composite measure of mathematics which measures a range of mathematical skills, whereas, 58 studies used single measures of mathematical ability (such as counting, or cardinality). Therefore, it is plausible that the mathematical activities parents undertake in the home with their children do not relate to all mathematical skills equally. For example, theoretically, we would expect counting activities to support children's counting skills, but not their shape recognition skills. Considering both the way studies categorise home mathematical activities and the different ways they measure mathematical ability, it is perhaps unsurprising that the results of studies are so inconsistent.

Thirdly, it is possible that the differing sample characteristics between studies, in part, explains the inconsistency in findings. The age of children included in the studies is one possible sample characteristic that may be influencing the disparities in results across studies. For example, some studies look at children aged three-to four-years (Liu et al., 2019) whereas, other studies use the same home mathematical activity questions with children aged six-to seven- years (Lefevre et al., 2009). It is conceivable that the mathematical activities parents do with their children vary considerably from age three- to age seven- years. This is because the developmental appropriateness of activities will change as children become older, for example counting activities may be more appropriate for younger children, whereas older children may focus more on arithmetic skills. Furthermore, during this time children begin formal schooling, where schools may give direction for home mathematical learning, thereby influencing the type and frequency of home mathematical activity. It is also possible that the benefits of home mathematical activities vary across age. Therefore, these differences in findings could also be due to the differences in age of the children included across studies. A further sample characteristic that may influence the inconsistent findings is SES. As discussed above, few studies have explored home mathematical activities in a socially diverse sample. However, a meta-analysis found that a positive relation between home mathematical activities and mathematical ability was larger in high-SES families than low-SES families (Dunst et al., 2017), therefore making it plausible that the differing SES makeup of samples influences the strength of relation between home mathematical activities and mathematical ability.

To summarise, the evidence suggests that the frequency that parents engage in home mathematical activities with their child may be important for supporting children's mathematical development. However, there are a number of unanswered questions given the limitations of current research both in their measurement of home mathematical activities (i.e., questionnaires measuring frequency) and in their sample characteristics (i.e., not using a diverse SES sample).

1.7.3. Executive Functions

So far in this literature review, opportunity-level mechanisms by which SES may impact early mathematical ability have been discussed. Executive functions are a propensity level mechanism by which SES attainment gaps in early mathematical ability may develop, that will now be discussed.

Executive functions are higher order cognitive skills that enable individuals to engage in deliberate, goal-directed behaviour, and respond to situations flexibly (Diamond, 2013). Three core executive functions are thought develop in childhood: working memory, inhibitory control, and cognitive flexibility (Lehto et al., 2003). Firstly, working memory enables an individual to hold in mind, process, and manipulate information. Working memory is comprised of two processing domains: phonological working memory which processes auditory information (e.g., being able to hold a string of digits in memory and recall them backwards) and visuospatial working memory which processes visual information (e.g., remembering the order in which a set of blocks lit up, and recalling the order they were tapped backwards) (Alloway et al., 2006). Secondly, inhibitory control enables an individual to ignore information that is distracting or resist pre-potent but incorrect responses, for example in a mathematical word problem, an individual would have to inhibit less relevant information in order to successfully focus on the vital information to solve the problem (Diamond, 2013). Thirdly, cognitive flexibility enables an individual to adapt their thoughts and behaviours in response to changes in their goals or environment, for example, sorting through cards by set rules such as sorting by colour and then switching to sort by shape (Blakey et al., 2016).

Executive functions develop rapidly in the preschool years and continue to develop into late adolescence (Anderson, 2002; Diamond, 2013). Working memory and inhibitory control are considered the first executive functions to develop, with pre-cursors to these skills being demonstrated in infancy (for example, infants develop the ability to sustain and direct attention in a goal-directed way and hold information in mind for brief durations). Cognitive flexibility is understood to develop later as it incorporates both working memory and inhibitory control; for instance, in order to switch rules, the current rule must be maintained in memory while inhibiting the old rule (Davidson et al., 2006; Diamond, 2013; Garon et al., 2008). This thesis will focus primarily on working memory and inhibitory control as these executive functions emerge and develop rapidly during the early years. Further justification for this is that cognitive flexibility is thought to be more important for advanced mathematics than basic mathematics. For example, where a mathematical problem has multiple stages which require switching between tasks and operations to complete the problem (Cragg & Gilmore, 2014). Thus, cognitive flexibility is likely to be important for mathematical skills which develop after the preschool years.

The development of executive functions are influenced by environmental factors. A review of evidence from neuroscience shows that environmental factors including stress, nutrition, and cognitive stimulation, which have a socioeconomic gradient, have been linked to the development of the prefrontal cortex which is responsible for higher order cognitive control, like working memory and inhibitory control (Hackman & Farah, 2009). Blair and Raver (2016) highlight that low-SES families often experience more financial and social pressures than high-SES families. Caregivers who are exposed to these stressors are more likely to have increased psychological stress, which in turn has been shown to affect parent-child interaction, including increased irritability, detachment, and harsh and inconsistent parenting. These behaviours have been linked to poorer executive function development (Raver et al., 2013; Rosen et al., 2019; Ursache et al., 2015). Furthermore, children in low-SES families are more likely to be exposed to chronic stressors such as noise, household chaos, and family conflict, which can result in an increase in stress hormones which are linked to prefrontal brain development responsible for executive functioning (Blair, 2010). Given this information, it is unsurprising that a meta-analysis looking at the relation between SES and executive functions in children aged between 2- and 18- years found an overall small effect size for the relation between SES and executive functions, with children from higher-SES families having better executive functions than their lower-SES peers (Lawson et al., 2018). However, the meta-analysis highlights that the majority of studies which have looked at the influence of SES on executive functions have not been conducted in a diverse SES sample. When the meta-analysis looked only at studies with a diverse-SES sample, they found a medium effect size between SES and executive functions. This highlights firstly, that executive functions are influenced by SES and secondly, the need for diverse SES samples when trying to understand socioeconomic gradients in executive functions.

There is some debate regarding whether working memory and inhibitory control should be considered separate facets of cognition or be considered part of a broader single 'executive function' factor in early childhood. Much of the research looking at executive functions has been conducted with adults and adolescents where executive function components appear distinct (Huizinga et al., 2006; Miyake et al., 2000). However, research in younger children has found working memory and inhibitory control to be strongly correlated (Lee et al., 2013; Lerner & Lonigan, 2014). Therefore, it has been suggested that in young children, individual components of executive functions are indistinguishable and that they are better conceptualised as a single factor (Lee et al., 2013; Lerner & Lonigan, 2014; Wiebe et al., 2008, 2011). Conversely, other research has found that considering working memory and inhibitory control as separate factors was a better fit to the data than considering them as a single factor in three- to five- year- olds (Lerner & Lonigan, 2014; Miller et al., 2012). A strength of considering executive functions as a single factor is that it creates a 'purified' executive function measure (Wiebe et al., 2011). To elaborate, executive functions regulate other non-executive abilities, such as language skills, which means single executive function measures are vulnerable to measurement error caused by these non-executive skills, which is referred to as 'task impurity' (Miyake et al., 2000). Creating a single factor with task scores helps to decrease this measurement error. However, creating a single factor may not be advantageous for individual differences research because it does not enable us to look at the role of specific executive functions on academic skills. This is pertinent because both working memory and inhibitory control have been found to differentially predict academic outcomes (Bull et al., 2008; Lerner & Lonigan, 2014). Creating a single executive function factor would limit the conclusions that can be drawn about the influence of individual executive functioning abilities on academic attainment. Thus, given that the focus of this thesis is on individual differences, and specifically, to understand mechanisms that may underpin attainment gaps, this thesis will rely more on the latter approach, considering executive functions as separate facets of cognition. This will enable us to say with greater specificity what mechanisms may explain socioeconomic attainment gaps.

1.7.3.1. Executive Functions and Mathematical Attainment

Executive functions have been identified as an important domain general skill for mathematical ability (Bull & Lee, 2014; Cragg & Gilmore, 2014; Geary, 2004). When considering how specific executive function skills may support mathematical development, it is likely that working memory supports early mathematical skills by enabling children to retrieve numerical facts, and to maintain and process numerical information to successfully carry out mathematical operations. Inhibitory control may support early mathematical development by enabling children to ignore distracting information while focusing on the mathematical problem and helping them to suppress prepotent but incorrect strategies when solving a problem.

To date, the majority of research which has explored the relation between executive functions and mathematical ability has been conducted with children once they have begun formal education, and more so in older children and adults. This research has found both working memory and inhibitory control to be associated with mathematical ability (Raghubar et al., 2010; Yeniad et al., 2013). Research which has explored the role of executive functions on specific mathematical skills has found executive functions to be important for written mathematics, verbal calculation, arithmetic, number word problems, and mathematical reasoning (Agostino et al., 2010; Brookman-Byrne et al., 2018; Cragg & Gilmore, 2014; Gilmore et al., 2015; Lubin et al., 2013; Saracho & Spodek, 2008). Less is known about the influence of executive functions on specific foundational mathematical skills.

Looking to the findings of research which has been conducted in younger children, two-year- olds' executive function skills have been found to predict both mathematics and literacy ability at age five years, with the relation being stronger for mathematics than literacy (Mulder et al., 2017). Both working memory and inhibitory control, as separate facets, have been found to relate to mathematical ability in preschoolers (Blakey et al., 2020; Blakey & Carroll, 2015; Cahoon, et al., 2021). Thinking about specific working memory domains, both visual short-term memory and working memory in preschool age children have been found to specifically predict mathematical achievement at age five, six, and seven (Bull et al., 2008). A meta-analysis looking at the relation between inhibitory control and mathematical ability found a medium effect size in children aged between two- and a half-years to six- and a half-years old (Allan et al., 2014). A meta-analysis looking at the relation between working memory and mathematical ability found a medium correlation, however, this included studies with participants aged from preschool to adulthood (Peng et al., 2016). Together, this suggests that both working memory and inhibitory control play an important role in the development of early mathematical skills.

Bringing this together to consider the main aim of the thesis, to identify mechanisms by which SES influences early mathematical ability, there have been some studies which have explored whether executive functions do mediate the relation between SES and mathematical ability. In older children, executive function has been found to mediate the relation between SES and mathematical ability (Ellefson et al., 2020; Lawson & Farah, 2017). In younger children, executive functions have also been found to partially account for the relation between SES and mathematical ability (Blakey et al., 2020; Fitzpatrick et al., 2014). However, these studies took a binary approach to measuring SES, separating SES into 'high' and 'low' categories. This binary approach reduces the conclusions that can be drawn about the influence of executive functions as a mechanism across the SES spectrum. Furthermore, all of these studies looking at executive functions as a mechanism to explain SES gradients in mathematical ability have treated executive functions as a unitary construct as opposed to separate facets of cognition. This limits our understanding of the role that individual executive functions may play.

1.7.4. Verbal Ability

Verbal ability is a second propensity-level mechanism by which SES may influence mathematical ability. There are many types of language skills which are encompassed by the term 'verbal ability', and these include receptive and expressive vocabulary, semantics, grammar, and pragmatics. Focusing on all elements of verbal ability is beyond the scope of this thesis. Therefore, this thesis will focus specifically on receptive vocabulary given that (i) there is extensive evidence showing SES disparities in vocabulary, and (ii) receptive vocabulary is one of the first verbal ability skills to develop and is related to the development of other language skills (Duff et al., 2015; Fenson et al., 2007; Shavlik et al., 2021), and (iii) of the research which has explored the relation between verbal ability and early mathematical ability, most research has focused on the role of receptive vocabulary, thus, there is currently a larger evidence base for the relation between receptive vocabulary and mathematics than other aspects of language (e.g., Cahoon et al., 2021; Purpura et al., 2011). Receptive vocabulary refers to the words that someone can understand and respond to, even if they are unable to produce those words expressively themselves (Burger & Chong, 2011). Vocabulary develops rapidly throughout a child's second year of life. To highlight this, infants at 19 months are producing, on average, 105 words, but by 25 months, they are able to produce, on average, 304 words (Song et al., 2018).

Despite rapid development in verbal ability in infancy and toddlerhood, from as young as 18 months of age there are significant disparities in the amount of words children hold in their vocabulary (Fenson et al., 2007; Shavlik et al., 2021; Song et al., 2018). It is well documented that these disparities in early vocabulary size are strongly influenced by a child's SES, with children from lower-SES households holding significantly fewer words in their expressive and receptive vocabulary than children from higher-SES households (Arriaga et al., 1998; Dollaghan et al., 1999; Fernald et al., 2013; Morisset et al., 1990). Furthermore, like in mathematical skills, these early vocabulary size disparities not only remain but widen over time (Fernald et al., 2013; Walker et al., 1994).

The development of verbal ability is thought to be greatly influenced by a child's environment (Olson et al., 2011). Pace et al. (2017) highlighted three main environmental pathways by which the SES influences children's verbal ability. Firstly, the *quantity* of words children hear is related to their verbal ability development, with children who are exposed to more words having a larger vocabulary (Hoff, 2003; Huttenlocher et al., 1991). By age four, children from higher-SES families have heard approximately 20-30 million more words than children from lower-SES families (Hart & Risley, 1995). Although, more recently Sperry et al. (2018) failed to replicate this word gap, finding that there is large variation in vocabulary environments within each socioeconomic band. This has contributed to a shift from focusing on quantity to quality. Secondly, the *quality* of language interactions parents have with their child has been identified as being a predictor for verbal ability. For example, the complexity of vocabulary used and the contingency of the language interaction (i.e., talking to a child about what their attention is focusing on, such as if a child was looking at an orange, talking to the child about the orange) is related to vocabulary and has SES gradients (Huttenlocher et al., 2010; McGillion et al., 2017; Rowe, 2012). Thirdly, the opportunities for language learning in the environment through resources, such as books and games, have been associated with the development of verbal ability and is influenced by SES (Rodriguez et al., 2009).

1.7.4.1. Verbal Ability and Mathematical Ability

A wealth of research has demonstrated the importance of verbal ability for literacy skills (Cheng & Wu, 2017; Duff et al., 2015; Ricketts et al., 2007), with verbal ability found to mediate the relation between SES and reading comprehension (Cheng & Wu, 2017). However, less is known about the importance of verbal ability for mathematical skills. Conceptually, the development of mathematics is closely related to the development of verbal ability. A child's ability to map vocabulary to number marks the transition from non-symbolic to symbolic number understanding (Xenidou-Dervou et al., 2015). An example of this at the most basic level is that when children first learn the count sequence, they are essentially learning words with an arbitrary meaning. However, learning these words is essential for children to learn the cardinal principle, which gives number words meaning and is a cornerstone of subsequent mathematical development (Wynn, 1995). Indeed, children's cardinal principle development between 30-60 months is strongly related to their verbal ability (Negen & Sarnecka, 2012). Following this, children will begin to learn more specialist mathematical language, including comparative terms (e.g., "more" vs. "less"; "bigger" vs. "smaller"), and mathematical operators (e.g., "add", "subtract"). This demonstrates how verbal ability is directly intertwined with mathematical learning.

LeFevre et al. (2010) identified verbal ability as a key pathway to mathematical development in children aged four- to six- years, which is typically the age when children have begun formal education. Indeed, when looking at four- to six-year-olds, there are significant relations between verbal ability and the individual mathematical skills, including: verbal counting, one-to-one correspondence, cardinality, subitizing, number comparison, set comparison, number order, number identification, set to numerals, and story problems (Purpura & Ganley, 2014). When looking at before children have begun formal education, verbal ability also appears to be an important predictor of mathematical ability in preschoolers (Cahoon, et al., 2021; Purpura et al., 2011). More recently, verbal ability has been found to mediate the relation between SES and mathematical ability in children both after they have begun formal education (von Stumm et al., 2020), and in preschool (Slusser et al., 2019). However, the majority of children in Slusser et al.'s (2019) study had university educated parents, meaning the sample was skewed to higher-SES children and thus limiting the conclusions that can be drawn about whether verbal ability is an important mechanism by which SES gaps in mathematical ability arise across the SES spectrum.

1.8. Research Gaps

The current literature review has highlighted that socioeconomic disparities are visible in mathematical skills before children begin formal education. These disparities not only persist but widen throughout formal education, and into adulthood, with profound consequences for a range of later outcomes including income, health, and wellbeing. Identifying the mechanisms that give rise to this attainment gap will be essential for developing interventions that may help to decrease, and ultimately perhaps close, the SES attainment gap. While it is evident that a multitude of factors play a role in the socioeconomic gradient in early mathematical ability, this literature review has identified three plausible mechanisms at an opportunity- or propensity- level: home mathematical activities, executive functions, and verbal ability. There are three reasons in particular to focus on these factors. Firstly, all three factors have been found to relate to preschoolers' mathematical skills, and each tends to show socioeconomic gradients. Secondly, these three factors reflect more proximal mechanisms that may directly explain SES attainment gaps. Finally, these factors are all potentially malleable to intervention. However, there are a number of limitations with current research which must be addressed in future research before these factors can be recommended for interventions that may help to decrease, and ultimately perhaps close, the SES attainment gap.

Firstly, much of the research to date has explored a single factor rather than multiple factors together in a single study. It is vital that research considers multiple mechanisms in a single study as there are likely to be multiple pathways through which SES influences mathematical ability. Secondly, the majority of current research has been conducted in middle- to high- SES samples, thus substantially limiting our understanding of these factors across the SES spectrum. If we are to understand mechanisms which cause SES gradients in mathematical ability, it is imperative that we use diverse SES samples. Thirdly, most research to date exploring factors that affect mathematical ability has been with children once they have started formal education. This is problematic as mathematical ability begins developing prior to the start of formal education, and by the time children begin formal education socioeconomic disparities in their mathematical attainment are already visible. Therefore, these three factors must be addressed to enable us to identify mechanisms that may explain SES attainment gaps in early mathematical ability.

1.9. Overall Aims of this Thesis

The overall aim of this thesis is to identify mechanisms by which socioeconomic disparities in early mathematical skills arise. This thesis will explore mechanisms at an opportunity level, exploring the relation between frequency of home mathematical activities and early mathematical skills, as well as exploring propensity level or 'child-level' factors, looking at children's executive functions (working memory and inhibitory control) and verbal ability as mechanisms by which SES attainment gaps arise. These factors were chosen as the literature has identified them to be the most proximal to mathematical development and they have been consistently related to SES. Furthermore, these factors were chosen as it is likely that if evidenced to be mechanisms, they may be susceptible to interventions to decrease early attainment gaps. This will be the first investigation of multiple opportunity- and propensity-level mechanisms that may influence SES gradients visible in mathematical ability before children begin formal education in diverse SES samples. This thesis will yield valuable knowledge on the mechanisms by which socioeconomic attainment gaps in early mathematical ability arise. It is hoped that this knowledge will lay the foundations for the development of early interventions to reduce the socioeconomic attainment gap in early mathematical ability.

Chapter Two
Exploring Home Mathematical Activities as a Mechanism by which Socioeconomic Attainment Gaps in Early Mathematical Ability Arise: A Secondary Data Analysis

Socioeconomic attainment gaps in mathematical ability are visible before children begin school. Home mathematical activities have been associated with early mathematical ability, but less is known about their relation to SES. The aim of this study was to explore whether the frequency of home mathematical activities explains the relation between SES and mathematical ability before children begin school. A secondary aim of the study was to explore how parent cognitions (i.e., how important they believe mathematics to be, and their own mathematical self-efficacy) may relate to home mathematical activities, and whether there are socioeconomic gradients in these cognitions. The final sample for our analysis consisted of 82 3- and 4-year-olds and their parent. Frequency of home mathematical activities did not vary by SES, nor did it relate to children's mathematical ability. Parent cognitions about mathematics did not vary by SES or relate to the frequency that parents engaged in home mathematical activities with their child. The limitations and implications of these findings are discussed, along with recommendations for future research.

2.1. Introduction

Socioeconomic attainment gaps in mathematical ability are visible before children begin formal education, and not only persist but widen over the duration of schooling (Caro et al., 2009; Sirin, 2005). This is pertinent because early mathematical skills have been found to be one of the strongest predictors of later academic attainment (Duncan et al., 2007). In addition, mathematical ability in adulthood is associated with income, health, and well-being (National Numeracy, 2015). Thus, identifying the mechanisms underpinning early attainment gaps is crucial if we are to prevent SES disparities in early mathematical ability embedding and widening.

Given that disparities in mathematical skills begin to develop before children begin formal education (Blakey et al., 2020;), it is likely the early home environment plays a key role in early mathematical development (King et al., 2020). A wide range of factors in the early home environment – from the cognitive resources available to the quantity and quality of parent-child interactions – vary by SES and strongly influence a number of developmental outcomes, including academic attainment (Bradley & Corwyn, 2002; Hackman et al., 2015; King et al., 2020; Lowe et al., 2013; Rosen et al., 2020).

Frequency of home mathematical activities is one element of the home environment which may explain socioeconomic differences in early mathematical ability. Frequency of home mathematical activities refers to how often parents engage in activities that involve mathematics with their child in the home. It is thought that the more frequently parents engage in home mathematical activities with their child, the more exposure to mathematical concepts the child will gain, and the more opportunities there will be for children to practise their mathematical skills (Andrews et al., 2021). Therefore, it is often assumed that children who engage in a higher frequency of home mathematical activities will have higher mathematical ability than their peers who engage in a lower frequency of home mathematical activities. There is some evidence to support the assumption that frequency of home mathematical activities is important for early mathematical ability. For example, a seminal study by Lefevre et al. (2009) found that frequency of home mathematical activities significantly related to mathematical ability in children aged between five- and eight- years-old. Since then, a number of studies have explored the relation between frequency of home mathematical activities and early mathematical ability, with some studies replicating the positive relation found by Lefevre et al. (2009) (e.g., LeFevre et al., 2010; Susperreguy et al., 2020) however, other studies have found no relation (Cahoon et al., 2021; Missall et al., 2015; Zhou et al., 2006), or even a negative relation (Ciping et al., 2015). A recent meta-analysis looking at the home mathematical environment found an overall positive relation between the home mathematical environment and children's mathematical ability, though this relation was small (r = .13) (Daucourt et al., 2021).

Frequency of home mathematical activities is particularly interesting when thinking about the mechanisms by which SES may influence early mathematical skills. This is because there is large variation in the amount of home mathematical activities parents engage in, with some parents reporting not engaging in any home mathematical activities, while other parents report engaging in multiple home mathematical activities daily (DeFlorio & Beliakoff, 2015; Lefevre et al., 2009). It is possible that this variation is related to SES. As outlined in the literature review, there is ample evidence showing SES differences in the amount of learning resources in the home (Crosnoe et al., 2010). However, less is known about whether SES specifically influences the frequency that parents engage in home mathematical activities. Of the research which has explored this, DeFlorio and Beliakoff (2015) found small differences in the frequency of home mathematical activities between middle-SES and low-SES families. More recently, Napoli et al. (2021) found socioeconomic gradients in home mathematical activities when sex and age were controlled for. However, this study did not look at whether this SES variation in home mathematical activities was related to children's mathematical ability. This suggests that SES does relate to the frequency of mathematical activities parents do in the home, but as yet, we still do not know for sure whether home activities are a key mechanism through which attainment gaps in mathematical ability arise.

It is important to recognise, and explore, the broader reasons why parents may engage in home mathematical activities that are both within their control and not within their control. If we better understand the motivations and barriers to parents engaging in home mathematical activities, we will be better able to support parents to engage in these activities. Dowker (2021) emphasises the importance of considering parents own cognitions about mathematics when exploring the home mathematical environment. These cognitions include parent beliefs about how important mathematical learning is and their own self-efficacy and confidence around mathematics. Considering parent cognitions when exploring home mathematical activities is important because a range of evidence has demonstrated a relation between parental attitudes and children's outcomes. For example, children of parents with negative attitudes towards mathematics have lower mathematical ability than children of parents with positive attitudes towards mathematics (Soni & Kumasi, 2015). Furthermore, parents' own mathematical self-efficacy has been found to influence their children's mathematical ability, with children of parents who display mathematical anxiety having poorer mathematical ability than children of parents who do not display mathematical anxiety (Maloney et al., 2015). Together, these studies suggests that children of parents who feel more confident in their own mathematical skills, and see mathematics positively, are more likely to have higher mathematical ability than children of parents who do not. While it is not clear the precise mechanisms through which this relation may arise, it gives a broader context to why we might see differences in levels of mathematical learning activities between parents.

Looking specifically to the few studies which have explored parent cognitions in relation to home mathematical activities, Sonnenschein et al. (2012) found that parent beliefs about the importance of mathematics positively related to frequency of home mathematical activities, but that parent self-efficacy did not. However, Sonnenschein et al. (2012) did not include a measure of children's mathematical ability meaning it was not possible to ascertain whether this was related to mathematical ability. Susperreguy et al. (2020) found that parents who held more positive numeracy attitudes engaged in a higher frequency of mathematical activities than parents who did not, and that mathematical activity frequency did predict children's mathematical skills.

There is reason to think that SES may influence parent cognitions about mathematics. Indeed, a review by Elliott & Bachman (2018) suggest that parent cognitions could be a key mechanism to explaining SES disparities in early mathematical ability. Higher-SES parents have been found to be more likely to rate the home environment as being important for early mathematical learning in comparison to lower-SES parents (DeFlorio & Beliakoff, 2015). Skwarchuk et al., (2014) found that higher household income was related to more positive numeracy attitudes. Similarly, Susperreguy et al. (2020) found more highly educated parents held more positive numeracy attitudes, measured by asking parents about how they feel about their own mathematical skills. Therefore, it is conceivable that the higher importance placed on home mathematical learning by higher-SES parents, as well as their more positive attitudes towards mathematics, than lower-SES parents, translates into an increased amount of home mathematical activities. However, to date, no research has explored whether parent cognitions i) vary by SES, and ii) whether this relates to frequency of mathematical activity, thus acting as a pathway by which SES may influence frequency of home mathematical activities, in a single study with a diverse SES sample.

The aim of the current study was to analyse secondary data to explore whether home mathematical activities are a mechanism by which SES attainment gaps in early mathematical ability emerge. The secondary data for this analysis was kindly shared by Dr Jo Van Herwegen containing measures of SES, frequency of home mathematical activities, and mathematical ability. The analysis had three research questions: firstly, is there a socioeconomic attainment gap in early mathematical ability? Secondly, does frequency of home mathematical activities explain socioeconomic disparities in early mathematical ability? And thirdly, do parent cognitions (i.e., parent beliefs about the importance of mathematics and parent self-efficacy of mathematics) explain the relation between SES and frequency of home mathematical activities? The hypothesised relations are displayed in Figure 2.1.

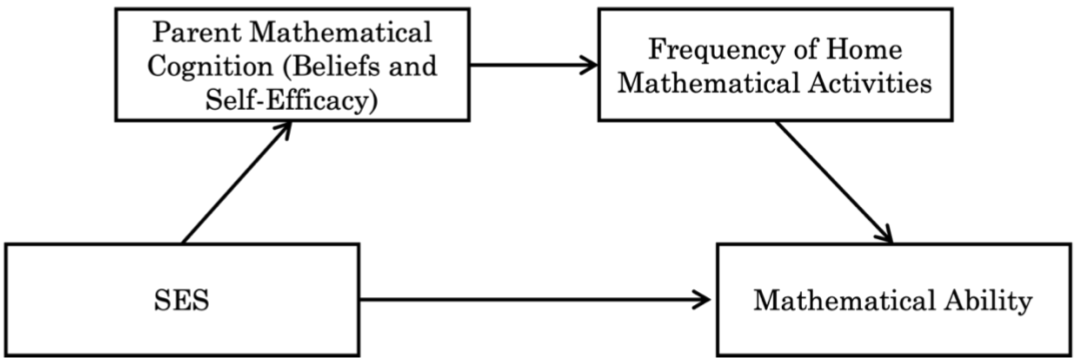


Figure 2.1 Hypothesised mediation to explain the relation between SES and mathematical ability, with the relation going through parent mathematical cognitions, and frequency of home mathematical activities.

2.2. Method

2.2.1. Participants

Three hundred and eighty-five children participated in this study. Children were recruited across fourteen preschools (seven private nurseries and seven free local authority settings) in Greater London. Data for 102 children was removed because they did not meet the inclusion criteria (see Table 2.1 for further details). Parents were asked to complete a questionnaire about the home mathematical environment (return rate = 29%). The current study focuses on the baseline data for children who had a questionnaire returned. Questionnaire return significantly differed by SES ($t_{(236)} = -2.09$, $p = .038$), with children with a returned questionnaires more likely to be from higher-SES households ($M = 7.12$, $SD = 3.35$), than children without a questionnaire ($M = 6.09$, $SD = 3.65$). The final sample used in our analyses comprised of 82 3- to 4-year- olds (46 males, 36 females, *M*age = 44.38 months, 5.22, range = 36-57 months). SES was calculated using mother's highest level of education which was available for 75 children. Mother's education ranged from 0 (no formal education) to 11 (doctoral degree). The socioeconomic distribution of the sample, displayed in Figure 2.2, shows that children in the study were predominantly from higher-SES households.

Table 2.1 Reason for participant exclusion

Reason for Exclusion	*N*
Low English language understanding	33
Diagnosis of developmental issues/ not in typical range of the British Ability Scale	19
No child assent	24
Child did not complete baseline assessments	26
Parent did not return their questionnaire on the home mathematical environment	201
Total number of children who met inclusion with returned questionnaire	**82**

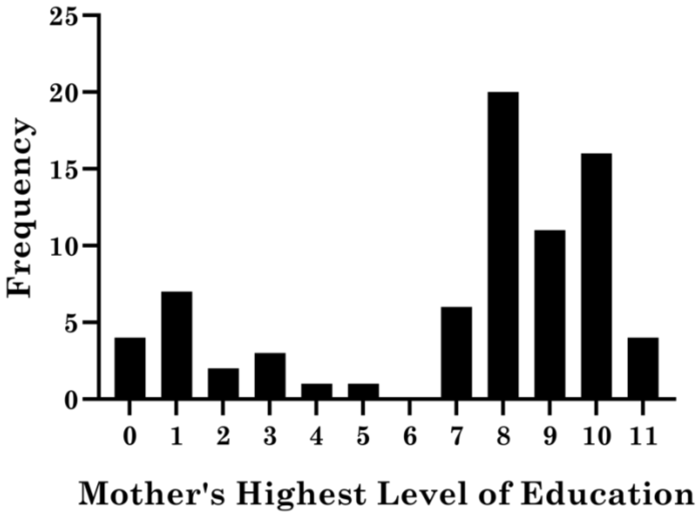


Figure 2.2 The distribution of mother's highest level of education in the sample (where 0 is no formal qualifications and 11 is the highest level of education).

2.2.2. Measures and Procedure

Data for this study was taken from a wider intervention study which measured a range of cognitive skills. The current secondary data analysis focuses on the baseline data. The variables in this dataset include children's mathematical ability measured using the standardised TEMA-3, as well as variables collected from a parent questionnaire including demographic information, mother's highest level of education, frequency of home mathematical activities; and parent cognitions: parent beliefs about mathematics and parent mathematical self-efficacy (see Appendix 1a for questionnaire items).

Mathematical ability was measured using the TEMA-3. The TEMA-3 measures a range of early mathematical skills including numeracy, number comparison, numeral literacy, mastery of number facts, calculation skills, and understanding of concepts, in children aged three to eight years. One point was awarded for each correct answer, and the task ended when five incorrect answers in a row were given. Total scores were calculated by adding up the scores for each correct trial (ranging from 0 to 72). The TEMA-3 has high reliability and validity (Bliss, 2006).

Frequency of home mathematical activities was measured with a questionnaire adapted from questionnaires used by Lefevre et al. (2009), Segers et al. (2015), and Skwarchuk et al. (2014). Parents rated how frequently they engaged in 23 home mathematical activities with their child – for example, counting objects, referring to time, and practicing simple sums. Frequency was measured using a five-point Likert scale with the answers ranging from 'not at all' to 'several times per day' (coded zero to four respectively). Total scores were calculated by adding up the scores for each question (ranging from 0 to 92).

Parent mathematical beliefs was measured with a questionnaire adapted from Sonnenschein et al. (2012), as well as questions developed by the research team. Parents rated how strongly they agreed or disagreed with seven statements relating to their beliefs about the importance of mathematics – for example, mathematics is a worthwhile and necessary subject, a strong mathematical background helps in adult life, and it is important for preschoolers to develop their mathematical skills. Beliefs about mathematics was measured using a five-point Likert scale with the answers ranging from 'strongly disagree' to 'strongly agree' (coded one to five respectively). Total scores were calculated by adding up the scores for each question (ranging from 0 to 35).

Parent mathematical self-efficacy was measured with a questionnaire adapted from Sonnenschein et al. (2012). Parents rated how strongly they agreed or disagreed with seven statements relating to their own mathematical self-efficacy – for example, when I was in school, I enjoyed mathematics, I am confident in my mathematical abilities, I find mathematical activities enjoyable. Mathematical self-efficacy was measured using a five-point Likert scale with the answers ranging from 'strongly disagree' to 'strongly agree' (coded one to five respectively). Total scores were calculated by adding up the scores for each question (ranging from 0 to 35).

2.3. Results

2.3.1. Descriptive Statistics

Descriptive statistics and correlation analyses were conducted using SPSS. Data was first examined to check the assumptions for the planned parametric statistical tests. All variables were visually inspected using histograms which revealed that mathematical ability was positively skewed, and that SES had a bimodal distribution. Frequency of home mathematical activities, parent beliefs, and parent self-efficacy were normally distributed. Therefore, both Spearman and Pearson correlations are reported in the correlation table. The correlations in bold indicate whether Pearson or Spearman correlation coefficients should be interpreted, which also corresponds to which correlation is reported in the text.

SES was transformed into a binary categorical variable with scores 0 to 5 categorised as 'low SES' and scores 6 to 11 categorised as 'high SES'. Descriptive statistics for the variables of interest, as well as correlation coefficients, are shown in Table 2.2. Figure 2.3 which displays the variation in frequency of home mathematical activities reported by parents.

Table 2.2 Correlation Coefficients for All Measures (Raw Scores).

		N	*M (SD)*	1	2	3	4	5
1. Mother's Education	High Low	57 18	8.86 (1.16) 1.61 (1.46)		.32**	**-.09**	**.04**	**.09**
2. Mathematical Ability		82	56.60 (13.79)	**.33****		.13	-.07	.01
3. Mathematical Activities		82	31.44 (8.12)	-.15	**.12**		**.49*****	**.27***
4. Parent Beliefs		82	26.94 (8.92)	-.01	**-.12**	.21		**.60****
5. Parent Self-Efficacy		82	10.56 (6.79)	.07	**.05**	-.05	**.40****	

Note. Spearman correlations are displayed in the bottom left corner and Pearson correlations are displayed in the top right corner. The correlations in bold meet the assumptions and should be interpreted. *N* = number of participants for each measure. *M* = mean, *SD* = standard deviation. *p < .05. **p < .01. ***p<.001.

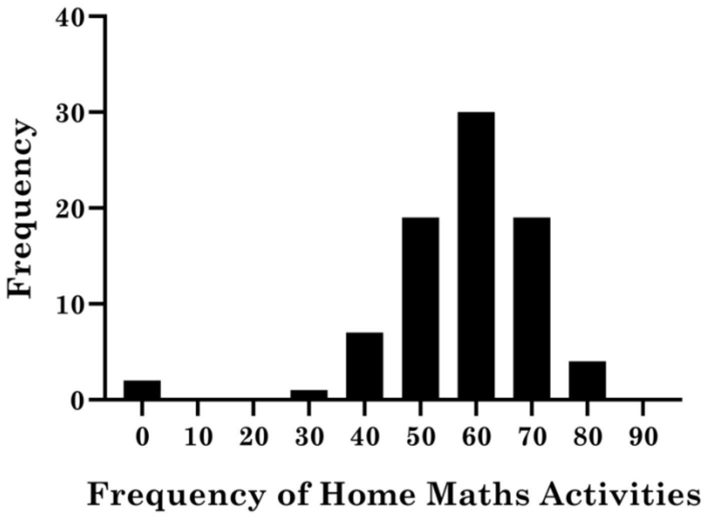


Figure 2.3 The distribution of the frequency of home mathematical activities reported by parents.

2.3.2. Was there an SES attainment gap in early mathematical ability?

Spearman's correlation analysis revealed a socioeconomic attainment gap in early mathematical ability, with children from lower-SES households having lower mathematical ability than children from higher-SES households ($r_s(73) = .33$, $p = .004$).

2.3.3. Was there an SES gradient in frequency of home mathematical activities and parent cognitions?

There was no significant correlation between SES and frequency of home mathematical activities ($r_s(73) = -.09$, $p = .444$), parent beliefs about mathematics ($r_s(73) = .04$, $p = .765$), or parent mathematical self-efficacy ($r_s(73) = .09$, $p = .455$).

2.3.4. Did home mathematical activities correlate with early mathematical ability?

There was no a significant correlation between frequency of home mathematical activities and children's mathematical ability ($r_s(80) = .12$, $p = .266$).

2.3.5. Did parent cognitions correlate with frequency of home mathematical activities?

There was a significant correlation between frequency of home mathematical activities and parent beliefs about mathematics ($r_s(73) = .49$, $p < .001$). However, parent mathematical self-efficacy did not correlate with frequency of home mathematical activities ($r_s(73) = -.05$, $p = .681$).

2.4. Discussion

The current study had three main aims: firstly, to establish whether there was a socioeconomic attainment gap in early mathematical ability; secondly, to explore whether frequency of home mathematical activities explains the socioeconomic attainment gap; and thirdly, to explore whether parent cognitions (i.e., parent mathematical self-efficacy and beliefs about the importance of mathematics) explained variation in frequency of home mathematical activities. As expected, the study found socioeconomic disparities in mathematical skills before children begin formal education, with children from higher-SES families having higher mathematical skills than children from lower-SES families. There was substantial variation in the frequency that parents engaged in home mathematical activities. However, in the current study frequency of home mathematical activities did not relate to early mathematical ability, nor did they vary by SES. Parents who believed mathematics to be more important engaged in a higher frequency of home mathematical activities than parents who believed mathematics to be less important. Mathematical self-efficacy did not relate to the frequency that parents engaged in mathematical activities with their child, nor did they vary by SES.

The first key finding was that SES differences in mathematical ability can be observed as early as age three years. This is poignant as it highlights that SES disparities in mathematical ability arise before children begin formal education. Therefore, if we are to decrease attainment gaps, it is important to understand mechanisms by which SES influences mathematical ability before children begin formal education, rather than once they have begun school. This is particularly relevant given the cumulative nature of mathematical learning, and that early interventions are often thought to reap larger rewards than later interventions (Shonkoff & Phillips, 2000).

The second key finding was that the frequency of home mathematical activities did not relate to early mathematical ability, nor did they vary by SES. This does not support our hypothesis that frequency of home mathematical activities is a mechanism by which SES attainment gaps arise. Taking firstly the finding that frequency of home mathematical activities did not significantly relate to early mathematical ability. This is somewhat surprising as it is contrary to the assumption that the more you practise, the better you will become. While the lack of relation is divergent to the findings of previous studies (Lefevre et al., 2009; Susperreguy, et al., 2020), it is not the first study to find no relation between frequency of home mathematical activities and mathematical ability (Cahoon, et al., 2021; Missall et al., 2015; Zhou et al., 2006).

Taking secondly the finding that there is not an SES gradient in home mathematical activities. It is possible that SES does not influence the frequency that parents engage in mathematical activities with their children. While previous studies have shown SES to influence the availability of learning resources in the home (Crosnoe et al., 2010), it is possible for parents to engage in the majority of home mathematical activities asked about in the current study without access to specific resources. Therefore, it is possible that SES is influencing children's mathematical ability through avenues other than frequency of activity, such as the availability of resources or the quality of parent-child learning interactions, rather than the quantity of those interactions. Another possible explanation for this finding is that we were hampered in our efforts to look at this because the sample was predominantly mid- to high- SES. Furthermore, the lack of variation across all types of mother education meant we had to dichotomise this variable making it less sensitive to detecting differences. It will therefore be important to replicate this finding in a more diverse and varied sample.

The third key finding was that parent beliefs about the importance of mathematics did relate to the frequency that they engaged in home mathematical activities, supporting previous research (Sonnenschein et al., 2012). However, parent beliefs did not vary by SES, suggesting that parent beliefs are not a route by which SES disparities in early mathematics emerge. Nevertheless, equipping parents with the knowledge of the importance of mathematics may encourage them to engage in a higher frequency of mathematical activities with their child.

The fourth key finding was that parent mathematical self-efficacy did not relate to the frequency that parents engaged in home mathematical activities, nor did it vary by SES. This is somewhat surprising as it seems intuitive that parents who have more confidence in mathematics will do more activities with their children. However, this finding is in line with Sonnenschein et al. (2012). It is possible that no relation is found due to the relatively basic nature of mathematical activities in the preschool years. It is conceivable that parent confidence in their own mathematical skills will have a stronger effect on home mathematical activities as children become older and the mathematical activities become increasingly complex. It is possible that parents experience other barriers to engaging in mathematical activities, which were not considered in the current study, such as time or resources.

There are several reasons to be cautious about the findings of the current study. Firstly, the home mathematical activities questionnaire used was developed and first implemented with a Canadian sample. It is possible that this questionnaire does not capture the types of home mathematical activities which take place in a UK home before children begin school. This would go some way in explaining why the current study does not find a relation between frequency of home mathematical activities and mathematical ability. Future research should explore whether a relation between frequency of home mathematical activities and mathematical ability is found in a home mathematical activities questionnaire specifically designed with UK parents, such as the recently developed home mathematical activities questionnaire by Cahoon, et al. (2021). Secondly, the current study utilised a standardised measure of mathematical ability which measures a range of mathematical skills, creating a final composite overall mathematical ability score. It is likely that specific mathematical activities nurture specific mathematical skill. For example, Sonnenschein et al. (2012) found that parents disproportionately do activities relating to counting with younger children. Therefore, it is possible that frequency of activities in younger children would relate to counting ability, rather than a composite measure of mathematical ability, like the one used in the current study. Future research exploring frequency of home mathematical activities should measure individual mathematical skills that develop in the preschool years such as counting and cardinality. Finally, it is important to interpret the SES findings of the current study with caution. This is because of the binary nature of the SES variable. Unfortunately, SES in the current sample was not normally distributed. In fact, the distribution of the data appeared bimodal, resulting in SES being categorised into the binary categories: 'high-SES' and 'low-SES'. It is conceivable that the binary measure of SES is not sensitive enough to capture SES relations in a way that a continuous measure of SES would enable. It is crucial that if we are to begin to identify and understand mechanisms by which SES influences mathematical ability, studies must recruit truly diverse socioeconomic samples to enable us to explore the influence of the full distribution of SES on plausible mechanisms.

To conclude, the current study highlights that socioeconomic attainment gaps in mathematical ability are visible prior to the start of formal education. While the study did not find frequency of home mathematical activities to be a mechanism by which SES attainment gaps emerge, it is important that home mathematical activities are not dismissed as a mechanism as a result of this study. Given that other studies have shown home mathematical activities to be important, it's plausible they could be a mechanism for SES attainment gaps, and activities may be relatively amenable to intervention. Future research should address the limitations of the current study, taking on the recommendations made to provide a clearer picture of the role of frequency of home mathematical activities for mathematical ability before children begin school.

Chapter Three
Reliably Measuring Cognition in Children from Low-Socioeconomic Backgrounds: A pilot study

Many studies using measures of cognition with young children have been conducted with children from middle- to high- SES backgrounds. We know that children from lower-SES backgrounds have, on average, lower ability than children from higher-SES backgrounds. Therefore, if we are to aim to recruit diverse SES samples, it is vital we test whether these measures are suitable for use in lower-SES samples. The aim of the current study was to pilot test measures of cognition that have previously been used with higher-SES children in a sample of low-SES children. This will enable us to determine whether these measures sufficiently capture variation in skill in low-SES children (i.e., ensuring that children are not at floor on a task). Forty children aged three- to four- years old from preschools in low-SES areas completed measures of working memory (Animal Recall and Backward Object Span), inhibitory control (Black/White Stroop), and mathematical ability (Counting and Give-a-Number). The pilot study found that the mathematical activity measures Counting and Give-a-Number, and the inhibitory control measure Black/White Stroop, successfully captured variation in low-SES preschoolers' ability. The working memory measures piloted did not capture variation, with low-SES preschoolers' performance being at floor. Recommendations for implementing measures of cognition in diverse-SES samples are discussed.

3.1. Introduction

To date, a large proportion of research exploring both cognitive skills and mathematical ability has been conducted in middle- to high- SES samples. While there has been some research which has specifically focused on low SES samples, very little research has focused on collecting data from children across the SES spectrum (see meta-analysis Lawson et al., 2018). This is a problem because it means many existing studies are not generalisable to children from a range of backgrounds, both in terms of the results, and also the developmental appropriateness of the tasks used. At a broader level, it limits our understanding of the acquisition and development of these skills in children from diverse SES backgrounds. In order to understand how socioeconomic disparities in early mathematical skills develop, it is paramount that children are recruited from diverse backgrounds and that the tasks used capture a range of abilities. Moreover, longitudinal research is required if we are to identify the temporal ordering of mechanisms by which SES impacts early mathematic skills (Jose, 2016).

From the few studies we have with diverse samples, the emerging consensus is that there is large variation in children's cognitive and mathematical abilities across the SES spectrum. When children begin school, children from lower-SES backgrounds are, on average, 4.6 months behind their peers from higher SES backgrounds (Educational Endowment Foundation, 2017). SES gradients in both mathematical and cognitive skills are evident in the preschool years, prior to children beginning formal education (Blakey et al., 2020; Lawson et al., 2018; Sirin, 2005). It is important that measures used with diverse SES samples adequately capture this variation. Given that many tasks previously used with preschoolers have been implemented with middle- to high- SES samples, it is imperative that studies aiming to recruit a diverse SES sample ensure their tasks are suitable for use with children across the SES spectrum.

Ensuring tasks are suitable for use with children from diverse SES backgrounds is particularly important when conducting research with preschool age children. The reason for this is that a number of core skills, including cognitive skills and mathematical skills, rapidly develop in the preschool years (Diamond, 2013; Rowe et al., 2012). Therefore, even without considering variation in skills across the SES spectrum, for many children for whom these skills are still developing, cognitive tasks can be challenging in terms of the basic memory and language skills required. Preschoolers from lower-SES backgrounds are likely to face additional challenges to their higher-SES peers. Firstly, they may struggle to understand the task instructions due to their, on average, smaller vocabulary and lower levels of comprehension (Farkas & Beron, 2004). Secondly, due to lower-SES children having, on average, lower cognitive skills, they may struggle to hold the task instructions in mind preventing them from successfully completing the task (Lawson et al., 2018). It is problematic if low performance on a task is the result of challenges arising from understanding basic instructions. This is because it would indicate that the task does not capture variation in the skill it is expected to be measuring. Therefore, lower-SES children may score at floor on a task not because they are at floor in that skill per se, but because the additional task demands are too complex to enable the required skill to be captured. In summary, if tasks are not suitable for children from across the SES spectrum, it will not be possible to elucidate the mechanisms by which SES disparities in early mathematical ability develop.

When aiming to identify mechanisms by which SES impacts mathematical development, it is not only important to select tasks that capture variation across the SES spectrum, but also tasks that will capture variation over time (Grammer et al., 2013). Ensuring tasks are suitable across the duration of longitudinal studies will enable the exploration of how these skills develop, and how different factors influence the growth of these skills. Therefore, when selecting possible measures, it is important to consider the ceiling of the task to ensure it is beyond the upper ability limit of children over time (i.e., task design should avoid the task no longer capturing variation of the skill, because the upper limit has been attained).

The aim of the current study is to pilot test a range of cognitive measures and mathematics measures to ensure that they i) capture variation in preschoolers from low SES backgrounds; ii) low SES preschoolers can understand the basic instructions to ensure the tasks are measuring that true ability and iii) they result in variation in performance across different ages. The pilot testing was essential to ensure the good measurement of these skills in a planned longitudinal study with children in the year before they begin formal school (aged three-to four- years). The longitudinal study will take measures at three time points (the beginning of the preschool year, the end of the preschool year, and the beginning of reception year). This will enable the identification of mechanisms by which SES gaps in mathematical ability arise in the year before children begin school, focusing on executive functions and verbal ability.

This pilot study will focus specifically on testing measures of working memory, inhibitory control, cardinality, and counting. We did not pilot test standardised measures of mathematical ability and verbal ability. This was because these tasks have already been successfully used in our lab with children from a range of SES backgrounds, and as part of their development have been tested in many children from a range of backgrounds and in children as young as age two. The pilot study will explore: i) whether there is a good distribution of scores on the tasks when implemented with low-SES children, ii) whether task performance increases as a function of age, as expected, iii) whether the executive function measures correlate with one another, as we would predict, and iv) whether the mathematics measures correlate with one another, as we would predict.

3.2. Method

3.2.1. Participants

Forty children were recruited from two nurseries in low-SES areas of South Yorkshire (23 males and 17 females, M_{age} = 47.68 months, SD = 5.51, range = 40-57). These nurseries were selected because they were located in areas in the most deprived Index of Multiple Deprivation (IMD) Decile and had a substantially higher than the average, 20.8%, number of pupils eligible for free school meals (FSM) (Department for Education, 2021a; Ministry of Housing Communities and Local Government, 2019) (see Table 3.1).

Table 3.1 Socioeconomic information for the preschools recruited

	Pupils eligible for FSM	IMD
Nursery 1	45%	1
Nursery 2	51%	1

Note. Index of Multiple Deprivation ranges from 1 (most deprived) to 10 (least deprived).

3.2.2. Measures and Procedure

Children were tested individually, completing tasks in a single 20-minute session in their preschool. Five tasks were piloted in the order: 1) Counting, 2) Animal Recall (working memory)/ Backward Word Span (working memory), 3) Black/White Stroop (inhibitory control), and 4) Give-a-Number (Cardinality). The Animal Recall Task was piloted with participants 1-19. However, due to low performance on this task that was evident almost immediately, an alternative working memory task, Backward Word Span, was piloted on participants 20-40. All participants were administered the Black/White Stroop, Give-a-Number, and the Counting task. Details of each measure are below.

Counting was measured using a forward enumeration task where children were asked to count out loud as high as they could, starting from one (up to a maximum of 42). The task was ended if the child gave the wrong number or skipped a number in the count sequence. The total score was the highest number correctly counted to from 1 (ranging from 0 to 42).

Working Memory: Animal Recall (McCormack et al., 2013). This task was used to measure working memory. Children were shown a sequence of familiar animals that appeared on the screen for one second. The animals were followed by a coloured smiley face appearing between each animal in the sequence. Children were required to say the colour of the smiley face out loud when it appeared on screen. At the end of the sequence, children had to recall the animals in the same order they were displayed. The task contained a short practise phase, followed by four trials at each span length, with spans ranging from one to five (up to 16 trials in total). To progress to the next span length, children had to correctly recall four trials at a span length (not necessarily in the correct order). Total scores were calculated by adding up scores for each correct trial (each correct list position was scored 0.25, with the total score ranging from 0 to 10).

Working Memory: Backward Object Span (adapted from Blakey & Carroll, 2015). Children were shown a span of familiar monosyllabic objects on a computer screen (e.g., tree, hat). When the object appeared on the screen, the experimenter spoke the name of the object aloud as it appeared. Each picture was followed by a one second inter-stimulus blank screen.

After children had been given the sequence of objects, they were asked to repeat the objects aloud in the backwards order they had been presented in (e.g., hat, tree). The task contained a short practise phase, followed by four trials at each span length, with spans ranging from one to four (up to 20 trials in total). To progress to the next span length, children had to correctly recall four trials at a span length (not in the correct order). Total scores were calculated by adding up scores for each correct trial (each correct list position was scored 0.25, with the total score ranging from 0 to 10).

Inhibitory Control was measured using the Black/White Stroop task (Vendetti et al., 2015). One white card and one black card were placed on a table directly in front of the child. Children were instructed to respond by touching the opposite colour card to what the experimenter said. Therefore, when the experimenter said 'black' the child should touch the white card, and when the experimenter said 'white' the child should touch the black card. After a short practice phase, children completed 12 trials presented in a fixed pseudorandom order (BA-BA-AB-BA-BA-AB). Total scores were calculated by adding up the scores for each correct trial (ranging from 0 to 12).

Cardinality was measured using the Give-a-Number task adapted from Wynn (1990). Children were given a basket of 15 toy strawberries, and were told they were the shopkeeper and the experimenter was the customer (who held an empty basket). The experimenter asked for n strawberries to be placed in their basket. *N* followed the order: 1, 2, 3, 4, 5, 8, 10. In between each trial, the experimenter emptied the basket back out. If the child did not place the correct number of strawberries in the basket, the trial was repeated a second time. The task ended if the child did not place the correct number of strawberries in the basket on the second repeated trial. Total scores were calculated by adding up the scores for each correct trial (ranging from 0 to 7).

3.3. Results

Firstly, the distribution of scores for each task were plotted on histograms and visually inspected (Figure 3.1). The histograms revealed that the task scores for Counting and Give-a-Number were normally distributed. The Black/White Stroop task scores were not normally distributed, with many children scoring zero, however, there were a range of scores on this task with a sizeable number of children scoring above zero. This indicates that these measures capture variation in low-SES preschoolers' skills. Histograms of the working memory measures Animal Recall and Backward Word Span tasks revealed an inadequate distribution, with the majority of children scoring zero. This indicates that these tasks do not capture variation in low-SES preschoolers' skills.

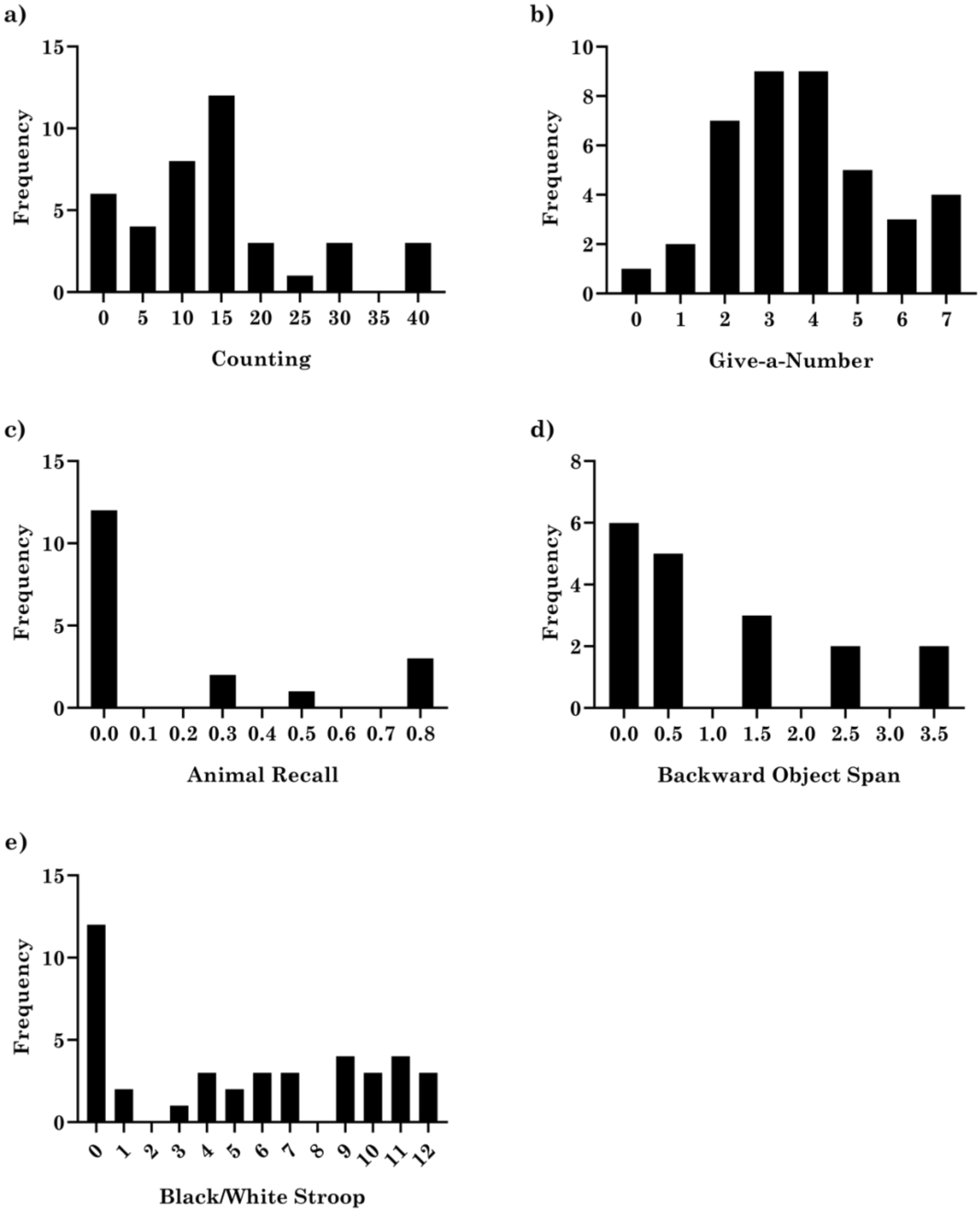


Figure 3.1 The distribution of scores for the tasks a) Counting, b) Give-a-Number, c) Animal Recall, d) Backward Object Span, e) Black/White Stroop.

Secondly, correlation analysis was run to explore i) variation according to age and ii) whether the mathematics tasks correlated as we would predict and whether the executive function tasks correlated as we would predict. Due to histograms revealing that the tasks Animal Recall, Backwards Object Span, and Black/White Stroop are not normally distributed, Spearman's Rho was used to conduct the correlation analysis reported in the text. Both Spearman's and Pearson's correlation coefficients can be seen in Table 3.2. The correlations in bold indicate whether Pearson or Spearman correlation coefficients should be interpreted, which also corresponds to which correlation is reported in the text. The purpose of pilot testing was to ensure that the tasks were able to be implemented with low-SES children, and not to look at relations between the variables as the pilot testing was not designed or powered to explore this. For this reason, we focus on the direction of correlation (i.e. positive or negative) rather than whether the correlation was statistically significant.

Table 3.2 Spearman's (bottom left) and Pearson's (top right) Correlation Coefficients for All Measures (Raw Scores).

	N	*M* (SD)	1	2	3	4	5	6
1. Age (months)	40	47.67 (5.51)		.32*	.10	-.37	-.03	.38
2. Counting	40	13.78 (10.75)	**.32***		**.49****	.31	.28	.71**
3. Give-a-Number	40	3.75 (1.77)	**.22**	.45**		.27	.39*	-.02
4. Animal Recall	18	0.18 (0.29)	**-.31**	**.29**	**.23**		.30	-
5. Black/White Stroop	40	5.30 (4.47)	**.04**	**.34***	**.39***	**.19**		-.36
6. Backward Object Span	18	0.94 (1.16)	**.23**	**.75*****	**-.05**	-	**-.30**	

Note. Spearman correlations are displayed in the bottom left corner and Pearson correlations are displayed in the top right corner. The correlations in bold meet the assumptions and should be interpreted *N* = number of participants for each measure. *M* = mean, *SD* = standard deviation. $p < .05$. $^{**}p < .01$. $^{***}p<.001$.

Task performance was positively correlated with age for the tasks Counting ($r_s(39)$ = .32), Give-a-Number ($r_s(39)$ = .22), and Backward Object Span ($r_s(17)$ = .23). This indicates that children's performance on these tasks increases with age as expected. Black/White Stroop very weakly positively correlated with age ($r_s(39)$ = .04). There was a negative correlation between age and the Animal Recall task ($r_s(17)$ = -.31).

We predicted that the tasks measuring executive function should positively correlate with one another which would indicate reliability. The inhibitory control task Black/White Stroop positively correlated with Animal Recall working memory task ($r_s(17)$ = .30), but negatively correlated with Backward Word Span working memory task ($r_s(17)$ = -.30). It was not possible to explore the correlation between the working memory tasks Animal Recall and Backward Object Span as they were not administered with the same children.

We predicted that the mathematics tasks would positively correlate with one another which would indicate reliability. There was a positive correlation between the Counting and Give-a-Number tasks ($r_s(39)$ = .49).

3.4. Discussion

The aim of this study was to develop measures of executive function and mathematics that could be used to accurately measure these abilities and their change over time in preschoolers from diverse SES backgrounds. The intention was to then use the most appropriate tasks as part of a longitudinal study. We therefore pilot tested working memory measures (Animal Recall and Backwards Word Span), an inhibitory control measure (Black/White Stroop), and mathematics measures (Counting and Give-a-Number) to see whether these measures capture variation in these skills in children from low-SES backgrounds.

The results showed that the Counting and Cardinality tasks successfully captured low-SES preschoolers' abilities, with low-SES preschoolers' task scores following a normal distribution. Furthermore, both of these tasks showed that task performance increased as a function of age, which is reassuringly implies that these tasks are capturing variation in these skills. This indicates that these tasks are adequate measures to be used in a diverse SES sample. Furthermore, these tasks have previously been used with older higher-SES children indicating that these tasks will be suitable for use with a diverse sample across the preschool year (Missall et al., 2015; Niklas & Schneider, 2014; Sella & Lucangeli, 2020; Spaepen et al., 2018).

Children's scores on the Black/White Stroop task did not follow a normal distribution, with many children scoring zero. However, a sizeable number of children did score above zero, and these scores were sufficiently dispersed across the distribution. This indicates that while this task may be challenging for children from low-SES backgrounds, this task is able to capture skill variation. It is important to recognise that the Black/White Stroop task only very weakly positively correlated with age. This raises some concern over whether this task is sufficiently capturing low-SES preschoolers' inhibitory control ability, as we would expect task performance to increase as a function of age. However, due to the constraints of pilot testing, this study had a very small age range. Therefore, it is important not to place too much emphasis on the relation between age and task scores. While pilot testing has revealed some concerns with using this task in low-SES preschoolers, there are few inhibitory control measures to choose from which are able to capture growth in inhibitory control across the preschool year. Moreover, a similar version of this task, the Day/Night Stroop, has been extensively used in preschool children (Montgomery & Koeltzow, 2010). Taken together, this indicates that the Black/White Stroop is suitable enough to be used in a diverse sample of preschoolers.

There was little variation in both working memory tasks, Animal Recall and Backward Object Span. The majority of low-SES children scored at floor on this task, suggesting that these tasks are not suitable for use with low-SES preschoolers. It is likely that both of these tasks were just too complex. The Animal Recall task required children to hold the information in mind while responding to distracting information. The Backwards Object Span task required preschoolers to say words in the opposite order they were presented, and simply understanding the concept of backwards may be a challenge for low-SES preschoolers. It is not clear whether poor task performance is due to: i) low-SES preschoolers having not yet developed these more complex working memory skills or ii) low-SES preschoolers do possess more complex working memory ability, but they are unable to grasp the task instructions which results in the task not accurately measuring their complex working memory. Further research is needed to explore this, and potentially develop working memory tasks for low-SES preschoolers which have lower vocabulary and comprehension demands in order to understand the task. Given that both working memory tasks piloted were not suitable for use in low-SES preschoolers, for the longitudinal study we chose to use a less complex working memory task, the Object Span Task, which does not require information manipulation. The Object Span Task has previously been used successfully with low-SES preschoolers in our lab and therefore, we are confident it will successfully capture variability in working memory for the planned longitudinal study.

In conclusion, this pilot study has established that the mathematics measures Counting and Give-a-Number, as well as the inhibitory control measure Black/White Stroop, successfully capture variation in low-SES preschoolers' ability. Therefore, this pilot testing coupled with previous research showing that these tasks can be successfully implemented with middle-high-SES children across the preschool year makes us confident in using these measures in a longitudinal study. The working memory measures piloted did not successfully capture variation, with child performance being at floor. Therefore, the working memory measures piloted will not be used in the proposed longitudinal study, and an alternative working memory measure which has previously been used with low-SES preschoolers in our lab will be used instead.

Note. Due to COVID-19, only baseline data was collected for the planned longitudinal study referred to in this chapter. The baseline data is reported in Chapter Four.

Chapter Four
How do Socioeconomic Attainment Gaps in Early Mathematical Ability Arise?

The socioeconomic attainment gap in mathematical ability is evident before children begin school and widens over time. Little is known about why this early attainment gap emerges. Two studies were conducted in 3- and 4-year-olds, to explore four possible factors that may explain why attainment gaps arise: working memory, inhibitory control, verbal ability, and frequency of home mathematical activities (N = 304, 54% female from a range of ethnic backgrounds but predominantly White British [76%]). Inhibitory control and verbal ability emerged as indirect factors in the relation between socioeconomic status and early mathematical ability, but neither working memory nor home mathematical activities did. These studies provide important insights about how the early attainment gap in mathematical ability may arise.

Note. This chapter is based on a manuscript currently under consideration following a revision at *Child Development*.

4.1. Introduction

The development of early mathematical skills is of great importance – not simply for building more advanced mathematical skills (Watts et al., 2014), but also because they are a strong predictor of overall academic attainment (Duncan et al., 2007). Poor mathematical skills have consequences far beyond academic attainment, including negative associations with health, income, and quality of life (National Numeracy, 2015). There are large individual differences in mathematical ability, and one factor which predicts these differences is SES, for example, maternal education at age four predicts mathematical achievement at age 15 (Ahmed et al., 2018). SES refers to an individual's combined social and economic resources, and position within society (Duncan & Magnuson, 2012). By the time children begin formal education, SES disparities in mathematics are already apparent, with children from lower-SES households having poorer mathematical ability, on average, than children from higher-SES households (Sirin, 2005). These early SES disparities not only persist, but increase, over the duration of a child's schooling (Caro et al., 2009), This has profound consequences: in the United Kingdom, one in four adults is estimated to have a lower mathematical ability than is needed for everyday life (OECD, 2013). It is therefore crucial to understand how SES disparities in mathematical ability first arise. Little is known about the mechanisms by which attainment gaps in mathematical ability emerge. This lack of understanding is a major obstacle to any attempt to narrow these gaps before they embed. Therefore, the present research aims to investigate multiple factors that might explain how SES attainment gaps in early mathematical ability arise.

When trying to understand how SES influences mathematical ability, it is particularly important to focus on *early* mechanisms. This is because mathematical learning proceeds incrementally: each numerical principle helps to form the foundations for later, more advanced principles. If a child lacks foundational mathematical skills (e.g., one-to-one correspondence), they will have difficulty building more advanced mathematical knowledge (e.g., basic addition) (Baroody et al., 2012). As a child falls behind in their mathematical learning, it becomes incrementally harder for them to catch up, resulting in an ever-widening gap between the lowest- and highest-ability children (Educational Endowment Foundation, 2017). Identifying the factors that give rise to this attainment gap will be essential for developing interventions that may help to decrease, and ultimately perhaps close, the SES attainment gap.

There are many factors that might explain why SES gaps in early mathematics arise. These include variables that influence the context into which a child is born (e.g., poverty, parent health); variables relating to the home and school environment; and child-level competencies (Ribner et al., 2019). Variables that influence the context in which a child is born are largely unchangeable without major, long-term shifts in policy at a global or national level. However, home- and child-level factors are often more malleable, and so provide plausible targets for interventions. In the present research, we focus on four home- or child-level factors that may explain mathematical attainment gaps: working memory, inhibitory control, verbal ability, and home mathematical activities. There are three reasons in particular to focus on these factors. Firstly, all four factors have been found to relate to preschoolers' mathematical skills and each tends to show socioeconomic gradients. Secondly, these four factors reflect more proximal mechanisms that may directly explain SES attainment gaps. Finally, these factors are all potentially malleable to intervention.

Working memory is the first proposed factor by which SES disparities in early mathematics may develop. Working memory is a core cognitive ability that enables us to maintain and manipulate information (Diamond, 2013). Working memory may support early mathematics by enabling children to retrieve numerical facts, and to maintain and process numerical information to successfully carry out mathematical operations. Working memory has been found to positively relate to preschoolers' mathematical ability (Blakey et al., 2020; Blakey & Carroll, 2015). In addition, environmental factors linked to SES – including stress, nutrition, and cognitive stimulation – are also linked to the development of brain areas responsible for higher-order cognitive control, including working memory (Hackman & Farah, 2009). Indeed, working memory itself has been found to vary by SES, with children from higher-SES families having better working memory, on average, than children from lower-SES families (Lawson et al., 2018). Furthermore, recent work has identified that preschool working memory mediates SES attainment gaps in middle childhood (Waters et al., 2021). Therefore, working memory is an important variable to examine in its role in early socioeconomic attainment gaps in mathematics.

Inhibitory control is the second proposed factor by which SES disparities in early mathematics may develop. Inhibitory control enables us to suppress distractions and resist prepotent but incorrect responses (Diamond, 2013). Inhibitory control may support early mathematical skills by helping children to ignore distracting information while focusing on a mathematical problem, and helping them to suppress prepotent but incorrect strategies when solving a problem. A meta-analysis found a medium effect size for the relation between preschoolers' inhibitory control and mathematical ability (Allan et al., 2014). Inhibitory control is a higher-order cognitive process, and as such is influenced by environmental factors, which have socioeconomic gradients (Hackman & Farah, 2009). Indeed, inhibitory control varies by SES, with children from higher-SES families having, on average, better inhibitory control than children from lower-SES families (Blakey et al., 2020; Lawson et al., 2018). It is therefore plausible that inhibitory control plays a role in socioeconomic differences in early mathematical skills.

There has been some debate regarding whether working memory and inhibitory control should be considered separate facets of cognition (e.g., Wiebe et al., 2011), or be considered part of a broader single factor in early childhood (e.g., Miller et al., 2012). Pertinent to individual difference research, researchers have stressed the usefulness in looking at working memory and inhibitory control separately, given they often differentially predict academic outcomes (Lerner & Lonigan, 2014). As we were focused on understanding specific factors that may underpin attainment gaps, we rely more on the latter approach to enable us to say with greater specificity what factors may explain mathematical attainment gaps.

Verbal ability is the third proposed factor by which SES differences in early mathematical ability may develop. Socioeconomic disparities in verbal ability are well documented: from as young as 18 months of age, children from lower-SES households have significantly fewer words in their vocabulary than children from higher-SES households (Fernald et al., 2013). SES differences in verbal ability have been linked to both the quantity of words children hear in the home, and the quality of language interactions (Hoff, 2003).

There has been a wealth of research demonstrating that children with higher verbal ability have more advanced reading skills (e.g., Duff et al., 2015) though less research has examined its role in mathematical skills. However, there is emerging evidence indicating that verbal ability may be important for early mathematical development. Conceptually, the development of mathematics is closely related to the development of verbal ability. A child's ability to map vocabulary to number marks the transition from non-symbolic to symbolic number understanding (Xenidou-Dervou et al., 2015). An example of this at the most basic level is that when children first learn the count sequence, they are essentially learning words with an arbitrary meaning. However, learning these words is essential for children to learn the cardinal principle (mapping number to quantity) which gives number words meaning and is a cornerstone of subsequent mathematical development (Wynn, 1995). Following this, children will begin to learn more specialist mathematical language, including comparative terms (e.g., "more" vs. "less"; "bigger" vs. "smaller") and mathematical operators (e.g., "add", "subtract"). This shows how verbal ability is directly intertwined with early mathematical learning. Indeed, LeFevre et al. (2010) identified verbal ability as a key pathway to mathematical development in children aged 4 to 6 years (see also Purpura et al., 2011). More recently, verbal ability has been found to mediate the relation between SES and mathematical ability (Slusser et al., 2019; von Stumm et al., 2020). While there is emerging evidence that verbal ability supports early mathematical ability, many studies tend to use receptive vocabulary as a marker of general cognitive ability. This makes it difficult to disentangle the roles of verbal ability and general cognitive ability. In order to understand whether verbal ability can explain mathematical ability above and beyond general cognitive ability, it is vital that studies control for general cognitive ability using an alternate variable to vocabulary, such as processing speed (Finkel et al., 2005). We opted to use processing speed in our study as it was age appropriate for young preschoolers (in contrast to IQ measures, which tend to be used from age five), and the task had minimal overlap with our key variables of interest.

Home mathematical activities are the fourth factor by which socioeconomic attainment gaps in early mathematical ability may develop. In recent years, there has been an increased focus on the role of the home environment in the development of mathematical skills, focusing on the frequency of the mathematical activities that parents do with their children in the home (Elliott & Bachman, 2018a). When we look at frequency, an intriguing but inconsistent picture emerges: substantial variation is found in the frequency with which parents report that they engage in home mathematical activities (from every day to not at all), and this frequency sometimes relates positively to children's mathematical ability (e.g., Kleemans et al., 2012; Lefevre et al., 2009); sometimes negatively (Blevins-Knabe et al., 2000; Ciping et al., 2015); and sometimes not at all (Missall et al., 2015; Zhou et al., 2006). Despite these contrasting findings, a recent systematic review found an overall positive relation between home mathematical practices and children's mathematical ability (Mutaf-Yıldız et al., 2020), suggesting that it is an important factor to consider when trying to explain how mathematical skills develop.

Currently, less is known about the influence of SES on the frequency of home mathematical activities. A moderate socioeconomic gradient has been found in the home learning environment more broadly (Melhuish et al., 2008). However, our knowledge of whether there are specific socioeconomic gradients in the frequency of home mathematical activities is limited due to the socioeconomically homogeneous samples that are often used in existing research. Of the few studies that attempted to look at this in socioeconomically diverse samples, SES has often been examined in a binary categorical way (medium and low SES) (DeFlorio & Beliakoff, 2015; Saxe et al., 1987). This binary approach will be less sensitive to capturing the full influence of SES on home mathematical activities. More recently, Napoli et al. (2021) deployed a more diverse SES sample to explore whether there is an SES gradient in frequency of home mathematical activities. They found a socioeconomic gradient in the frequency of home mathematical activities when age and sex were controlled for. However, the study did not explore whether this SES gradient in home mathematical activities related to variation in early mathematical ability. The importance of using diverse SES samples is further illustrated by home literacy research. SES gradients are clearly apparent in home literacy activities when diverse samples across the full SES spectrum are used (e.g. Phillips & Lonigan, 2009). Therefore, the use of more diverse samples is likely to be useful in elucidating whether there are genuine SES differences in home mathematical activities.

To summarise: previous research identifies four possible factors through which SES attainment gaps in early mathematics may arise: working memory, inhibitory control, verbal ability, and frequency of home mathematical activities. All four factors (i) vary by SES, and (ii) relate to mathematical ability. Moreover, it is vital these factors are considered together, as there are likely to be multiple pathways through which SES influences mathematics. Furthermore, it is most informative to look at these factors before children begin school, as this is when SES disparities first emerge. It is imperative that low SES groups are included - many prior studies have used predominantly middle-higher SES samples, greatly limiting what we can learn about socioeconomic attainment gaps. This research is essential in understanding how these attainment gaps emerge, and will help us to identify factors for longitudinal investigation.

To that end, the current chapter presents two studies which together aim to improve our understanding of how SES gaps in early mathematics develop. Both studies explore whether working memory, inhibitory control, verbal ability, and home mathematical activities indirectly explain the relation between SES and mathematics, above and beyond general cognitive ability (see Figure 4.1). Study Four aims to replicate the novel findings of Study

Three, and builds upon Study Three in three ways. Study Four recruits a truly diverse SES sample; it uses a more commonly used measure of frequency of home mathematical activities; and it uses multiple measures of SES, including both a neighbourhood-level and individual-level measure of SES.

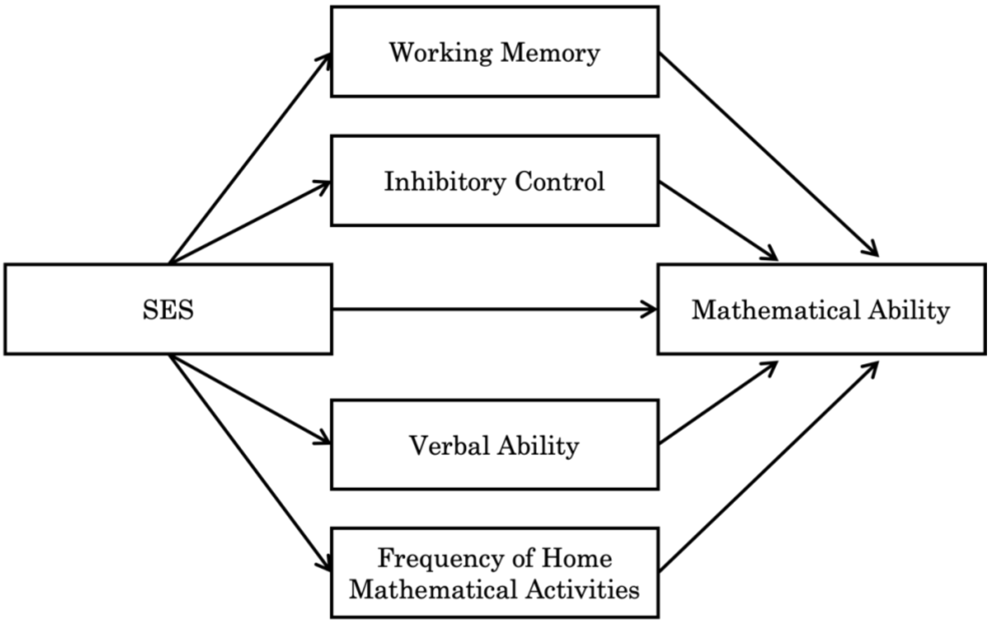


Figure 4.1 Hypothesised indirect effects model to explain the relation between SES and mathematical ability.

4.2. Study Three

The aim of study three was to explore possible factors that may explain the SES gap in early mathematics. Specifically, we examined the extent to which working memory, inhibitory control, verbal ability, and frequency of home mathematical activities explained socioeconomic gradients in a range of mathematical skills, including counting and cardinality. Counting was included as it is one of the first symbolic mathematical skills to develop (Wynn, 1990). Cardinality was included as it represents the milestone of children mapping number words to meaning (i.e., understanding that the last pronounced number denotes the numerosity of the set) and is vital for the development of subsequent mathematical skills (Geary et al., 2018). A comprehensive standardised index of mathematical ability was also included. To measure frequency of home mathematical activities, this study used a scale by Cahoon et al., (2021) that has recently been developed based on comprehensive parent interviews. To measure SES, the Index of Multiple Deprivation (IMD) was used: this is a precise composite measure of neighbourhood-level SES provided by the UK Office for National

Statistics (Ministry of Housing Communities and Local Government, 2019). We predicted that working memory, inhibitory control, verbal ability, and home mathematical activities would vary by SES, and would relate to early mathematical ability (see Figure 4.1).

4.2.1. Method

4.2.1.1. Participants

One hundred and seventy-four children (91 females, 83 males) participated. Children were recruited from six preschools in socioeconomically diverse areas of South Yorkshire, UK. Data were removed for 15 children (nine children did not complete the tasks due to distraction, three had a language impairment, and three had special educational needs). The final sample comprised 159 children (82 females, 77 males, *M*age = 44 months, *SD* = 3.95, range = 36-55 months). Sample size was determined through a power calculation to predict mathematical skills from our six predictors and one covariate in a hierarchical regression. The calculation indicated that 158 children would be required to detect a small-medium effect (f^2 = .09) with a power of .80 and alpha .05.

Parents were asked to complete a questionnaire about the home mathematical environment and their family demographics (see Appendix 1b for questionnaire items). Sixty-nine parents returned questionnaires (43% participation). The final sample of children who had questionnaires returned comprised 33 females and 36 males (*M*age = 44 months, *SD* = 4.14, range 36-52 months). The ethnicity breakdown for these children was 65% White-British, 20% Asian, 10% mixed ethnicity, 3% Black-African, 2% Kurdish. We were able to calculate SES for 87% of the sample (*N* = 138) using the Index of Multiple Deprivation (IMD) which was gained either from the parent questionnaire or from preschools. IMD scores ranged from 1 (most deprived) to 10 (least deprived). The socioeconomic distribution of the sample, shown in Figure 4.2, shows that the children in the study are predominantly from lower-SES households. Returned questionnaires were significantly more likely to be from households in higher-SES areas, and children with returned questionnaires also had significantly higher scores on the inhibitory control, working memory, verbal ability, counting, cardinality, and TEMA tasks. Further details of these comparisons are given in the Appendix 2a.

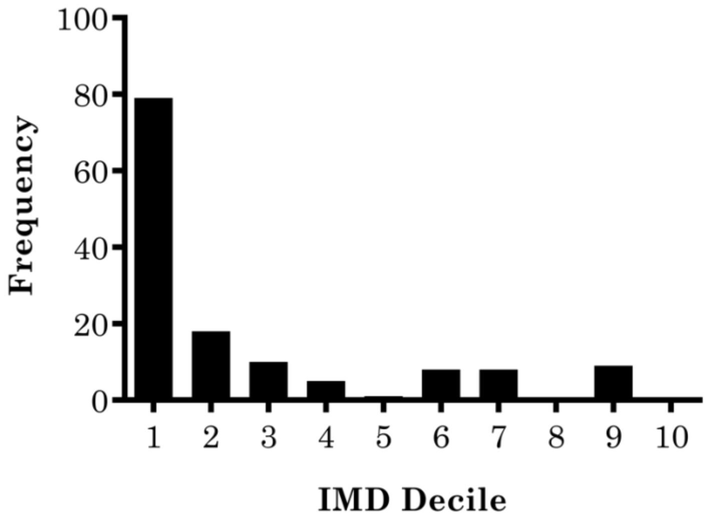


Figure 4.2 The SES distribution of the sample in study three as indexed by the neighbourhood deprivation measure IMD (where 1 represents the most deprived neighbourhoods and 10 represents the least deprived neighbourhoods).

4.2.1.2. Measures and Procedure

Children were tested individually, completing all seven tasks in a single 45-minute session in their preschool. Tasks were administered in the following fixed order: Give-a-Number (cardinality), Black/White Stroop (inhibitory control), Object Span (working memory), Bubble Popping (processing speed), TEMA (standardised mathematical ability measure), Counting, and BPVS (verbal ability). Children were rewarded with stickers for completing the tasks. Following the session, parents were asked to complete the home mathematical activities and family demographic questionnaire.

Frequency of home mathematical activities was measured with a questionnaire adapted from Cahoon et al. (2021). Parents rated how frequently they engaged in 26 home mathematical activities with their child – for example, counting objects, playing timed games, or teaching children about money. Frequency was measured using a five-point Likert scale with the answers ranging from 'activity did not occur' to 'almost daily' (coded zero to four respectively). Total scores were calculated by adding up the scores for each question (ranging from 0 to 104). The home mathematical activities questionnaire had high reliability (α = .90).

Working memory was measured with the Object Span task (adapted from Müller et al., 2012). Children were asked to copy a sequence of taps on six familiar objects (*book*, *spoon*, *leaf*, *peg*, *torch*, and *cup*) that were laid out in front of the child. The task contained a short practice phase, followed by three trials at each span length, with spans ranging from one to five (up to 12 trials in total). To progress to the next span length, children had to correctly copy two out of three trials in the correct order. Total scores were calculated by adding up the scores for each correct trial (each correct list position was scored 0.25, with the total score ranging from 0 to 15).

Inhibitory control was measured using the Black/White Stroop task (Vendetti et al., 2015). One white card and one black card were placed on a table directly in front of the child. Children were instructed to respond by touching the opposite colour card to what they were instructed to do. Therefore, when the experimenter said 'black' the child should touch the white card, and when the experimenter said 'white' the child should touch the black card. After a short practice phase, children completed 12 trials presented in a fixed pseudorandom order (BA-BA-AB-BA-BA-AB). Total scores were calculated by adding up the scores for each correct trial (ranging from 0 to 12). Good test-retest reliability scores for this kind of inhibitory control task have been reported (ICC: .87; Lagattuta et al., 2011).

Verbal Ability was measured using the British Picture Vocabulary Scale II (BPVS-II; Dunn et al., 1997). The BPVS is a standardised receptive vocabulary measure normed for children between 3 and 16 years. On each trial, four pictures were presented, and the experimenter read a word aloud. The child was asked to touch the picture that corresponded to the word. The task comprised a short training phase, followed by a testing phase of up to 14 sets of 12 words each, of increasing difficulty. To move onto a higher set, a child would need to give at least 5 correct answers in the current set. Total scores were calculated by adding up the scores for each correct trial (ranging from 0 to 168). The BPVS has been found to have high reliability (α = .93; Dunn et al., 1997).

Counting was measured using a forward enumeration task where children were asked to count out loud as high as they could, starting from one (up to a maximum of 42). The task was ended if the child gave the wrong number or skipped a number in the count sequence. The total score was the highest number correctly counted to from 1 (ranging from 0 to 42).

Cardinality was measured using the Give-a-Number task adapted from (Wynn, 1990). Children were given a basket of 15 toy strawberries, and were told they were the shopkeeper and the experimenter was the customer with an empty basket. The experimenter asked for *n* strawberries to be placed in their basket. *N* followed the order: 1, 2, 3, 4, 5, 8, 10. If the child did not place the correct number of strawberries in the basket, the trial was repeated a second time. The task ended if the child did not place the correct number of strawberries in the basket on the second repeated trial. Total scores were calculated by adding up the scores for each correct trial (ranging from 0 to 7).

Mathematical ability was assessed using the standardised TEMA-3 (Form A) (Ginsbery & Baroody, 2003). The TEMA-3 measures a range of early mathematical skills including numeracy, number comparison, numeral literacy, mastery of number facts, calculation skills, and understanding of concepts, in children aged three- to eight- years. One point was awarded for each correct answer, and the task ended when five incorrect answers in a row were given. Total scores were calculated by adding up the scores for each correct trial (ranging from 0 to 72). The TEMA-3 has high reliability and validity (Bliss, 2006).

Processing speed was included as a control variable, measured using a computerized 'bubble-popping' task. Children were instructed to 'pop' bubbles as fast as they could by touching bubbles that appeared on a touchscreen computer (Blakey & Carroll, 2015). Bubbles stayed on the screen until the child had touched them; when children 'popped' the bubble, a burst bubble appeared on the screen. Between trials there was an interval varying between 800 and 1200ms. Children completed a short practice block, followed by eight test trials. Children's median reaction time was calculated.

4.2.2. Results

4.2.2.1. Descriptive Statistics and Preliminary Analyses

Descriptive statistics and correlation analyses were conducted using SPSS. Mediation analyses were conducted using the PROCESS macro for R (Hayes, 2018). However, we note that as data were cross-sectional, we refer to the results as indirect effects and not mediation (see O'Laughlin et al., 2018 for a discussion). Data were first examined to check the assumptions for the planned parametric statistical tests. All variables were visually inspected using histograms and P-P plots which revealed that the data for SES, counting, TEMA, and inhibitory control were not normally distributed. Descriptive statistics for the variables of interest, as well as Spearman and Pearson correlation coefficients, are shown in Table 4.1. The correlations in bold indicate whether Pearson or Spearman correlation coefficients should be interpreted, which also corresponds to the correlation reported in the text. Hierarchical regressions looking at which variables predicted mathematical skills can be found in the Appendix 2a. As well as age, sex was controlled for in the analyses. This is because in older children, executive function only mediated the relation between SES and mathematical ability for boys, but not girls (Ellefson et al., 2020).

Table 4.1 Spearman's (bottom left) and Pearson's (top right) Correlation Coefficients for All Measures in Study Three (Raw Scores).

	N	*M (SD)*	1	2	3	4	5	6	7	8	9
1. SES (IMD)	138	2.57 (2.48)		-.09	.25**	.07	-.19*	.35**	.16	.02	.23**
2. Mathematical Activities	68	60.01 (16.07)	**-.03**		.04	**-.14**	**-.14**	**-.06**	**.13**	-.07	-.05
3. Inhibitory Control	155	4.34 (4.21)	**.18***	**.06**		.16*	-.13	.44**	.34**	.17*	.43**
4. Working Memory	154	3.51 (1.70)	**.12**	-.11	**.14**		**-.08**	**.32****	**.30****	.20*	.34**
5. Processing Speed	158	1210.92 (277.01)	**-.17***	-.13	**-.15**	-.13		**-.21****	-.19*	-.17*	-.29**
6. Verbal Ability	157	36.08 (13.49)	**.24****	-.13	**.42*****	.33***	-.19*		**.48****	.24**	.51**
7. Cardinality	159	3.55 (1.73)	**.12**	.10	**.34*****	.35***	-.17*	.49***		.38**	.62**
8. Counting	149	13.71 (7.29)	**.11**	**-.10**	**.15**	**.23****	**-.10**	**.26****	**.38*****		.60**
9. Mathematical Ability	157	6.20 (4.82)	**.21***	**-.11**	**.40*****	**.39*****	**-.29*****	**.53*****	**.59*****	**.52*****	

Note. Spearman correlations are displayed in the bottom left corner and Pearson correlations are displayed in the top right corner. *N* = number of participants for each measure. The correlations in bold meet the assumptions and should be interpreted. *M* = mean, *SD* = standard deviation. Mathematical Ability refers to the TEMA task. *$p < .05$. **$p < .01$. ***$p<.001$.

4.2.2.2. Was there an SES attainment gap in early mathematical ability?

Correlation analysis revealed a socioeconomic attainment gap in early mathematical ability, with children from more deprived neighbourhoods having lower TEMA scores than children from less deprived neighbourhoods (r_s(134) = .21, *p* = .015). However, SES did not correlate with counting or cardinality. Given that only the standardised measure of mathematical ability was correlated with SES, this will be the measure of mathematical ability used in the rest of the analyses, and will be referred to as “mathematical ability”.

4.2.2.3. Where do we see SES gradients?

There was a positive correlation between SES and inhibitory control (r_s(132) = .18 p = .039), processing speed (r_s(135) = -.17, p = .044) and verbal ability (r_s(134) = .24, p = .005). There were no significant correlations between SES and frequency of home mathematical activities or working memory.

4.2.2.4. Which variables correlated with mathematical ability?

There was a positive correlation between mathematical ability and inhibitory control (r_s(151) = .40, *p* < .001), working memory (r_s(150) = .39, *p* < .001), processing speed (r_s(154) = -.29, *p* < .001), and verbal ability (r_s(153) = .53, *p* < .001). Mathematical ability was not significantly correlated with frequency of home mathematical activities.

4.2.2.5. How can we explain the SES attainment gap in mathematical ability?

Mediation analysis was conducted to explore whether inhibitory control and verbal ability – two factors which both showed a socioeconomic gradient, and both predicted mathematical ability – indirectly predicted the relation between SES and mathematical ability. The first stage of the mediation analysis involved defining the model with direct and indirect effects; the second stage involved assessing the significance of the indirect effects. To assess the significance of our indirect effects model, we followed Preacher & Hayes (2008) procedure to calculate the 95% confidence intervals (CIs) of 10,000 bias-corrected bootstrapping analyses. This was chosen as it is considered a powerful method for detecting an effect while maintaining control over Type 1 errors, making it superior to other mediation procedures such as the Sobel test. A significant indirect effect is indicated if the CIs do not pass through zero.

In order to test whether inhibitory control and verbal ability indirectly explained the relation between SES and mathematical ability, a mediation analysis with two indirect effects was conducted. The model was fit with SES as the predictor; inhibitory control and verbal ability as indirect effects; and mathematical ability as the outcome variable. Processing speed, age, and sex were included as covariates (Figure 4.3). In the total effect model, SES had a significant positive effect on mathematical ability (β = .23, p = .006). In the indirect effects model, SES had a significant positive effect on inhibitory control (β = .27, p = .002) and verbal ability (β = .35, p < .001). Inhibitory control (β = .23, p = .009) and verbal ability (β = .30, p < .001) had significant positive effects on mathematical ability. The results of the bootstrapping procedure revealed that the indirect effect through inhibitory control (95% CI [0.01, 0.14]) and the indirect effect through verbal ability (95% CI [0.03, 0.21]) were significant, as the CIs did not pass through zero. The CIs indicated that inhibitory control and verbal ability were significant indirect effects in the relation between SES and mathematical ability. Pairwise contrasts of the indirect effects through inhibitory control and verbal ability (95% CI [-0.08, 0.15]) indicated that the paths did not differ significantly from each other, as the CIs passed through zero.

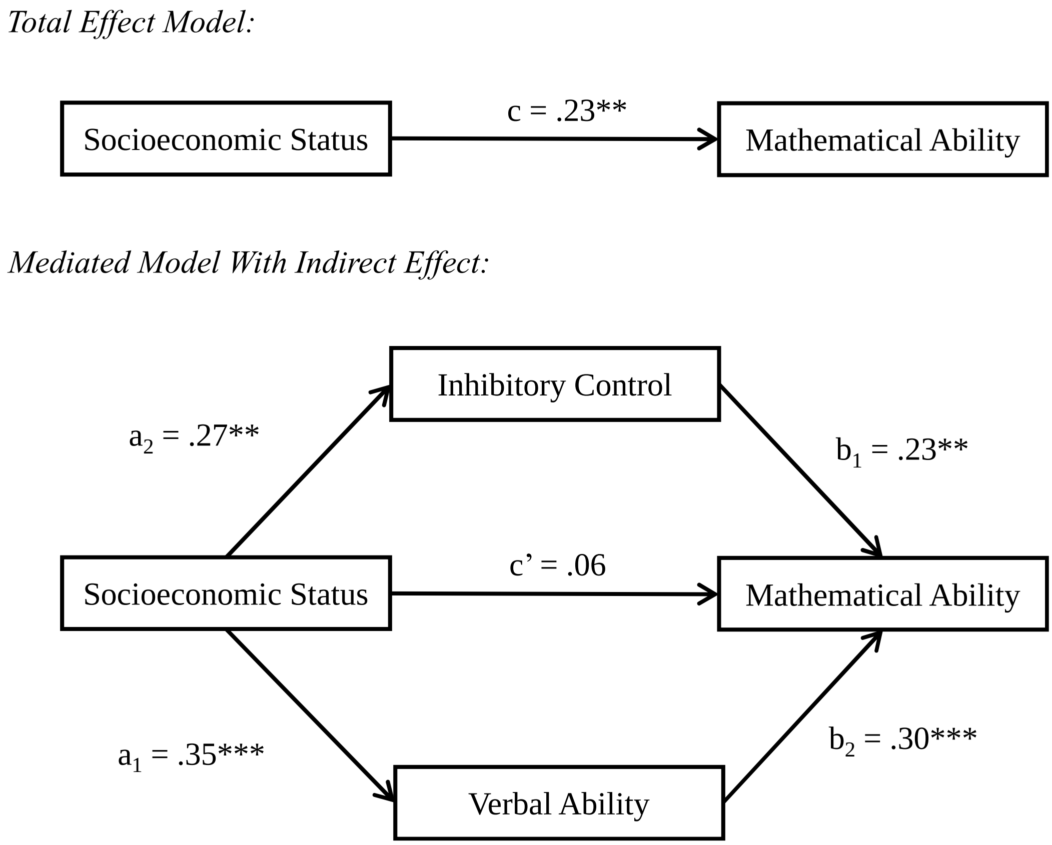


Figure 4.3 Indirect effects model showing the relation between SES (IMD) and mathematical ability, as mediated by inhibitory control and verbal ability, controlling for

processing speed, age and sex. Standardised beta weights are given. *P <.05, **p < .01, ***p < .001

4.2.3. Discussion

The aim of Study Three was to explore whether working memory, inhibitory control, verbal ability, and frequency of home mathematical activities are factors by which SES disparities in mathematical ability arise in the preschool years. Three measures of mathematical skill were assessed in the study: a standardised measure of general mathematical ability, and two measures of specific mathematical skills: counting and cardinality. The study found a socioeconomic attainment gap in the standardised measure of mathematical ability, but no socioeconomic gradients were found in counting and cardinality. Frequency of home mathematical activities did not vary by SES, and did not relate to any measure of mathematical ability. In contrast, working memory, inhibitory control, and verbal ability all positively correlated with mathematical ability – but socioeconomic gradients were only found in inhibitory control and verbal ability. As inhibitory control and verbal ability both correlated with mathematical ability and SES, we examined the extent to which they explained early attainment gaps in mathematical ability using mediation analyses. Both inhibitory control and verbal ability emerged as indirect predictors explaining the relation between SES and mathematical ability. This is some of the first research to show that verbal ability and inhibitory control may be key to explaining how mathematical attainment gaps arise.

Contrary to our hypotheses, neither working memory nor home mathematical activities varied by SES, suggesting these are not mechanisms by which SES attainment gaps in early mathematical ability develop. With regards to working memory, the fact that no socioeconomic gradient was found is at odds with some previous research (Lawson et al., 2018). One possible explanation for this difference is the age of the children tested. The majority of studies looking at SES gradients in working memory have been conducted with school-age children. Our study looked at preschoolers, and it is conceivable that SES gradients in working memory only emerge later in development. With regards to home mathematical activities, less is known about the role of SES, meaning that it is quite possible that the results of this study finding no SES gradient hold true. However, the lack of relation between SES and both working memory and home mathematical activities requires further exploration before these conclusions can be accepted with confidence. There are two reasons for this. Firstly, the sample in the present study was drawn from predominantly low-SES neighbourhoods. In order to be confident there are no SES gradients in working memory and home mathematical activities, a more diverse sample from across the full SES spectrum would be needed, to ensure enough variation to be able to detect possible differences. Secondly, the present study used neighbourhood indices of SES, rather than individual indices. Previous research into working memory found SES differences when using parent education, but not when using a neighbourhood deprivation measure (Hackman et al., 2014). While the IMD has been found to strongly relate to educational outcomes (Crawford & Greaves, 2013), it reflects the average SES for a neighbourhood. Therefore, using individual measures of SES (such as parental education) would give a more accurate measure of an individual child's SES.

The absence of relation between home mathematical activities and mathematical ability is particularly interesting, as many previous studies have reported this relation (see Mutaf-Yıldız et al., 2020 for review). More broadly, it seems to go against the notion that practicing a skill will lead to improvements in that skill. There are three further reasons to be cautious about this null finding. Firstly, it is important to note that while the current study was well powered overall, there was a low questionnaire return rate (43%). This meant that the study only had 51% power to detect a small-medium effect with home mathematical activities – although interestingly, the non-significant correlation between home mathematical activities and mathematical ability was small and *negative*. Secondly, study three's mostly low-SES sample may have meant there was little variation in home mathematical activities. Thirdly, study three used a new measure of home mathematical activities (Cahoon, et al., 2021a), while the majority of previous studies in this area have used a questionnaire based on the one developed by Lefevre et al. (2009). It may be that the questions developed by Lefevre et al. (2009) better capture the home mathematical activities relating to mathematical ability. So, while study three is not the first study to find no relation between home mathematical activities and mathematical ability (see also study one of this thesis, Missall et al., 2015; Zhou et al., 2006), there are grounds to be cautious when interpreting this null result.

In summary, the results of Study Three showed how early attainment gaps in mathematical skills emerge – specifically, that verbal ability and inhibitory control are crucial factors, but that working memory and home mathematical activities, surprisingly, are not. This is a hugely important finding, offering for the first time a clear understanding of how attainment gaps emerge in early development. However, given the relative novelty of these findings, it is important to test their robustness. Thus, we aimed to extend and replicate these findings in a further study.

4.3. Study Four

The aim of Study Four was to replicate the findings of Study Three. Like Study Three, Study Four explores the roles of working memory, inhibitory control, verbal ability, and frequency of home mathematical activities as mechanisms for explaining the SES attainment gap in early mathematical ability. However, in Study Four we made three methodological changes to ensure we could be confident in the results of Study Three. Firstly, Study Four aimed to recruit a socioeconomically diverse sample, to ensure we were capturing full variation across the SES spectrum. Secondly, the study took an individual measure of SES (mother's education) in addition to a neighbourhood measure. Thirdly, the study used a different measure of home mathematical activities, which has been used more widely in the existing literature. To measure mathematical ability, we retained only the standardised measure of mathematical ability, since Study Three only found a SES gradient on this broader and more comprehensive measure. All other measures remained the same.

4.3.1. Method

4.3.1.1. Participants

One hundred and forty-five preschoolers (80 females, 65 males, *M*age = 45.38 months, *SD* = 4.13, range = 37-52 months) participated. Of these, 113 preschoolers were recruited from five preschools in socioeconomically diverse areas of South Yorkshire, UK, and 32 children were recruited from a database of local families who had expressed an interest in participating in research. Sample size was determined through a power calculation to predict mathematical skills from five predictors and one covariate in a hierarchical regression. This indicated that 149 children were required to detect a small-medium effect (f^2 = .09) with a power of .80 and alpha .05.

Parents were asked to complete a questionnaire which collected data on demographic information, SES, and frequency of home mathematical activities. One hundred and six parents returned the questionnaire (73% participation, an increase from study three). The final sample of preschoolers who had questionnaires returned comprised 57 females and 49 males, Mage = 45 months, SD = 4.10, range 37-52 months. The ethnicity breakdown for the children was 86% White-British, 9% White-other background, 4% Asian, 1% mixed ethnicity. Comparing the preschoolers whose parents completed the questionnaire to those who did not indicated no differences on the experimental tasks. It was not possible to assess SES differences in questionnaire return, as we only had SES information for children who returned the questionnaire. Further details of these comparisons are given in Appendix 2b.

SES was calculated for each child using two measures: IMD and mother's highest level of education. IMD was derived from household postcode; for mother's education, the questionnaire asked for their highest level of education from a set list, ranging from 'no formal qualifications' to 'postgraduate degree or similar'. The European Qualification Framework (European Commission, 2018) was used to score the qualification, which ranged from 0 (lowest level of education) to 7 (highest level of education). The socioeconomic distribution of the sample, displayed in Figure 4.4, showed that the sample was socioeconomically diverse. In this study we focus on the more direct measure of SES, parent education (further details below).

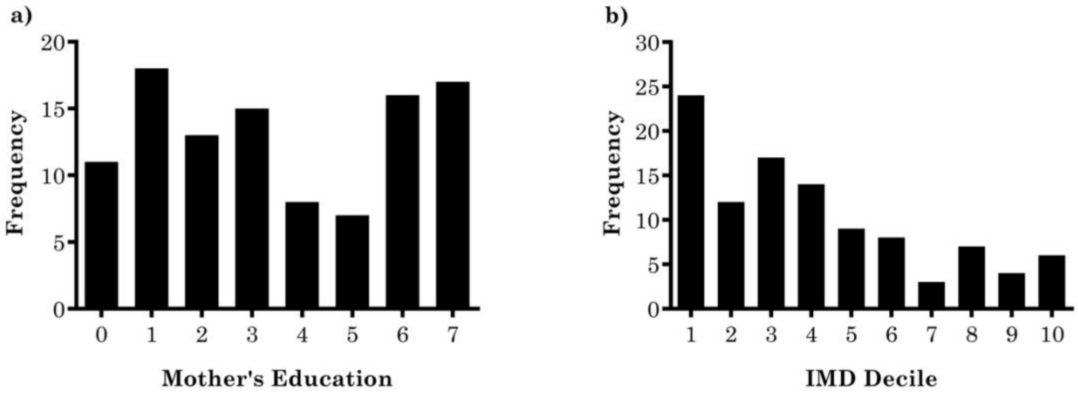


Figure 4.4 The SES distribution of the sample in study four as indexed by: a) mother's education (where 0 is the lowest and 7 is the highest level of education) and b) the neighborhood deprivation measure IMD (where 1 is the most deprived and 10 is the least deprived).

4.3.1.2. Measures and Procedure

Children completed all five tasks in a single session, either in their preschool or the university laboratory. Tasks were administered in a fixed order: Black/White Stroop (inhibitory control), TEMA (mathematical ability), Bubble Popping (processing speed), Object Span (working memory), and BPVS (verbal ability). Testing lasted approximately 40 minutes, and children were rewarded with stickers for completing the tasks. In addition, parents were asked to complete the questionnaire on home mathematical activities and family demographics.

Measures were identical to those in study three, with the single exception that frequency of home mathematical activities was measured using an alternative parent questionnaire (see Appendix 1c for questionnaire items). Parents were asked to rate how frequently they engaged in 21 mathematical activities with their child – for example, writing numbers, using calendars and dates, playing board games with a die or spinner (questions adapted from Lefevre et al., 2009). Frequency was measured using a five-point Likert scale, with the answers ranging from 'activity did not occur' to 'activity occurred almost daily' (coded 0 to 4 respectively). Total scores were calculated by adding up the scores for each question (ranging from 0 to 84). The home mathematical activities questionnaire had high reliability ($\alpha = .89$).

4.3.2. Results

4.3.2.1. Descriptive Statistics and Preliminary Analyses

Analyses were run in the same way as for study three. First, all variables were visually inspected using histograms and *P-P* plots which revealed that the data for mathematical ability, working memory, and inhibitory control were not normally distributed. Therefore, both Spearman and Pearson correlations are reported in the correlation table. The correlations in bold indicate whether Pearson or Spearman correlation coefficients should be interpreted, which also corresponds to which correlation is reported in the text. Descriptive statistics for the variables of interest, as well as Spearman and Pearson correlation coefficients, can be seen in Table 4.2. Hierarchical regressions looking at which variables predicted mathematical ability can be found in Appendix 2b. Age and sex were controlled for in the regression and mediation analyses.

Table 4.2 Spearman's (bottom left) and Pearson's (top right) Correlation Coefficients for All Measures in Study four (Raw Scores).

	N	*M (SD)*	1	2	3	4	5	6	7	8
1. SES (IMD)	104	4.05 (2.75)		**.51****	**-.04**	**-.17**	.28**	.07	**.37****	.28**
2. SES (Mother Education)	105	3.53 (2.42)	.49***		**-.08**	**-.22***	.28**	.16	**.39****	.30**
3. Mathematical Activities	105	32.32 (13.27)	.00	-.09		**-.07**	.02	.13	**-.06**	.11
4. Processing Speed	142	1306.10 (338.52)	-.21*	-.26**	.02		-.17*	-.13	**-.29****	-.29**
5. Inhibitory Control	145	5.83 (4.18)	**.30****	**.27****	**.05**	**-.16**		.16*	.34**	.50**
6. Working Memory	145	2.90 (2.01)	**.07**	**.17**	**.14**	**-.14**	**.17***		.33**	.49**
7. Verbal Ability	144	37.87 (13.30)	.35***	.39***	-.04	-.28**	**.36*****	**.33*****		.55**
8. Mathematical Ability	142	6.72 (6.03)	**.33****	**.40*****	**.11**	**-.29****	**.48*****	**.48*****	**.62*****	

Note. Spearman correlations are displayed in the bottom left corner and Pearson correlations are displayed in the top right corner. *N* = number of participants for each measure. The correlations in bold meet the assumptions and should be interpreted. *M* = mean, *SD* = standard deviation. $p < .05$. $^{**}p < .01$. $^{***}p<.001$.

4.3.2.2. Is there an SES attainment gap in early mathematical ability?

Correlation analysis revealed a socioeconomic attainment gap in early mathematical ability, as indexed by both IMD and mother's education. Lower levels of mathematical ability were evident in children living in more deprived neighbourhoods ($r_s(100) = .33$, p = .001), and in children whose mothers had a lower level of education ($r_s(101) = .40$, p < .001). For all further analyses, we used mother's education as the primary measure of SES, as this provides the most direct measure of family SES.

4.3.2.3. Where do we see SES gradients?

There were significant positive correlations between SES and inhibitory control ($r_s(103) = .27$, p = .005), and SES and verbal ability ($r_s(102) = .39$, p < .001). SES was not significantly correlated with either working memory or frequency of home mathematical activities.

4.3.2.4. Which factors correlated with mathematical ability?

Mathematical ability was significantly positively correlated with inhibitory control ($r_s(141) = .48$, $p < .001$), working memory ($r_s(141) = .48$, $p < .001$) and verbal ability ($r_s(140) = .62$, $p < .001$). It was not significantly correlated with frequency of home mathematical activities, indicating that frequency of home mathematical activities does not influence early mathematical ability.

4.3.2.5. How can we explain the SES attainment gap in mathematical ability?

To test whether inhibitory control and verbal ability mediated the relation between SES and mathematical ability, a mediation analysis with two indirect effects was conducted. The model was fit with SES as the predictor; inhibitory control and verbal ability as indirect effects; and mathematical ability as the outcome variable. Processing speed, age, and sex were included as covariates (Figure 4.5). In the total effect model, SES had a significant positive effect on mathematical ability ($\beta = .29$, p = .003). In the mediated model, SES had a significant positive effect on inhibitory control ($\beta = .29$, p = .005) and verbal ability ($\beta = .37$, p < .001). Inhibitory control ($\beta = .38$, p < .001) and verbal ability ($\beta = .30$, p = .001) had significant positive effects on mathematical ability. The results of the bootstrapping procedure revealed that the indirect effect through inhibitory control (95% CI [0.03, 0.21]) and the indirect effect through verbal ability (95% CI [0.04, 0.22]) were significant, as the CIs did not pass through zero. The CIs indicated that inhibitory control and verbal ability were significant indirect effects in the relation between SES and mathematical ability. Pairwise contrasts of the indirect effects through inhibitory control and verbal ability (95% CI [-0.13, 0.13]) indicated that the paths did not differ significantly from each other, as the CIs passed through zero.

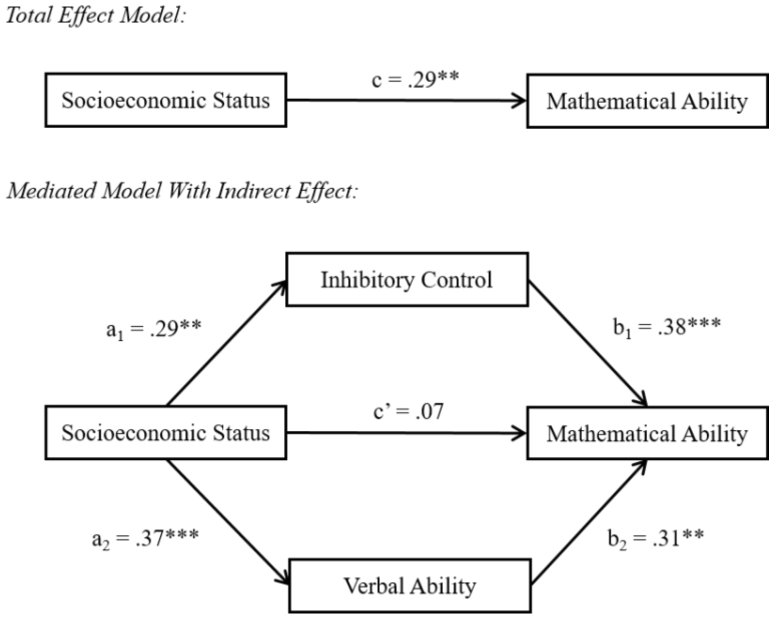


Figure 4.5 Indirect effects model showing the relation between SES (mother's education) and mathematical ability as mediated by inhibitory control and verbal ability, controlling for processing speed, age, and sex. Standardised beta weights are given. **P* <.05, ***p* < .01, ****p* < .001

4.3.3. Discussion

Study Four aimed to replicate the findings of study three using a more direct measure of SES, in a very diverse sample, and using a different scale to measure home mathematical activities. The results of study three were fully replicated: inhibitory control and verbal ability explained the relation between SES and mathematical ability; working memory significantly related to mathematical ability, but was not found to vary by SES; and the frequency of home activities did not vary by SES, or relate to frequency of mathematical ability. The replication of these findings suggests we can be more confident in our conclusions: that inhibitory control and verbal ability are indirect pathways by which we see SES attainment gaps in early mathematics, but working memory and frequency of home mathematical activities are not. We now discuss these findings in more detail.

4.4. General Discussion of Study Three and Study Four

The present research aimed to explore how early SES gaps in mathematical ability arise. Two studies were conducted to explore four possible factors: working memory, inhibitory control, verbal ability, and frequency of home mathematical activities. These factors were chosen as previous studies – which tend to look at them in isolation – found that they show SES gradients, and support children's mathematical skills. Study Three explored the role of these factors in explaining SES attainment gaps (as indexed by neighbourhood deprivation) on three measures of mathematical ability. Study Four replicated and extended this work, by using an individual measure of SES, and recruiting a highly socioeconomically diverse sample. Together, these studies provide a comprehensive exploration of how SES gaps in mathematical ability arise in early childhood. Importantly, both studies show that verbal ability and inhibitory control may be key to explaining early attainment gaps.

Four key findings emerged from this research. Firstly, there was a clear SES attainment gap in early mathematical ability. Secondly, verbal ability indirectly predicted the relation between SES and early mathematical ability. Thirdly, inhibitory control indirectly predicted the relation between SES and mathematical ability. Fourthly, working memory and home mathematical activities did *not* explain SES disparities in mathematical ability in either study. The fact that both studies – with different samples and different measures of SES and home mathematical activities – align on all four key findings suggests these results are robust. We now discuss each of these findings in more detail.

The first key finding was that a SES attainment gap in mathematical ability is apparent in children as young as three years of age. This is striking, and demonstrates that there are factors at play *before* children start school that lead to inequalities in outcomes. We know that mathematical development proceeds cumulatively (Baroody et al., 2012), meaning this early attainment gap is likely to not only remain, but to widen over time. This underlines the importance of targeting attempts to narrow this gap to the preschool years. The fact that SES gradients were not seen in basic measures of mathematical skills – counting and cardinality – is interesting, and worthy of further study. It may indicate that SES does not affect *all* kinds of mathematical skills equally. One explanation is that counting and cardinality are very basic tasks which children may complete without a real understanding of numerical magnitude (Sella & Lucangeli, 2020). In contrast, our measure of overall mathematical ability (the TEMA) required children to complete more complex tasks, and to use skills in combination (e.g., magnitude comparison and the use of arithmetic facts). Therefore, the mechanisms leading to SES gradients in mathematical skills may be ones that affect children's ability to integrate and use mathematical skills in concert. This is entirely consistent with the idea that SES may correlate with mathematical skills due to differences in children's executive functions (see Blakey et al., 2020). It would therefore follow that the biggest SES gradients on mathematical tasks would be seen on tasks that require children to use multiple mathematical skills in parallel.

The second key finding was that SES attainment gaps in early mathematics were indirectly explained by verbal ability. This is a key finding that bridges two important areas of research. Firstly, the finding that there are SES differences in verbal ability is consistent with a wealth of research demonstrating SES gradients in verbal ability (e.g. Fernald et al., 2013). Secondly, the findings are also consistent with a separate but growing body of evidence demonstrating the importance of verbal ability in the development of mathematical skills (Purpura et al., 2011; von Stumm et al., 2020). Verbal ability may support mathematical skills in multiple ways. Notably, language is essential for attributing meaning to mathematical concepts, and for expressing those meanings. It is also conceivable that verbal ability may modulate the cognitive demands of a task: for example, a child with poor verbal ability may not only have to meet the demands of the mathematical task itself, but also of learning, understanding and using unfamiliar language when completing the task (Meyer, 2000). By connecting these two separate strands of research – one examining SES gradients in verbal ability, and one on verbal ability and mathematical skills – the current study identifies verbal ability as an important factor for longitudinal investigation. If longitudinal research supports verbal ability as a mechanism, it is a plausible target path for interventions designed to reduce SES inequalities in early mathematics. The identification of verbal ability as a factor is particularly exciting, as there are already a number of verbal ability interventions which have been found to be effective (Marulis & Neuman, 2010).

The third key finding was that SES attainment gaps in early mathematics were also indirectly explained by inhibitory control. This finding is consistent both with previous research showing inhibitory control to be important for early mathematical development (Allan et al., 2014), and with studies that have found SES gradients in inhibitory control (Blakey et al., 2020; Lawson et al., 2018). To date, little is known about the mechanisms by which SES influences the development of inhibitory control. Recent longitudinal research may shed light on this. Waters et al. (2021) found that inhibitory control mediates the relation between SES and later mathematical ability, but that this relation did not hold when controlling for verbal ability. This finding suggests that verbal ability may be important in explaining SES differences in inhibitory control. Indeed, there is some evidence to suggest that verbal ability may help scaffold executive function development, by enabling children to monitor their thoughts and actions using inner speech (Daneri et al., 2019). In line with these findings and the current findings, we speculate that verbal ability may be a critical mechanism that explains how disparities in children's mathematical skills arise through its impact on executive function skills. Specifically, SES disparities in mathematical skills may begin by

SES influencing early verbal ability; this, in turn, may have a knock-on-effect on inhibitory control; which then goes on to influence mathematical ability. This speculation may inform a finer-grained model of how SES attainment gaps emerge, though it would be for future longitudinal research to definitively test such a model.

The fourth key finding was that SES attainment gaps in early mathematics were not explained by working memory or by home mathematical activities. Neither factor showed SES gradients, and thus neither could explain attainment gaps in mathematical ability. Both studies showed that working memory was positively related to mathematical ability, but that working memory did not vary by SES. This suggests that despite working memory's importance for early mathematical skills, it may not be a factor that drives SES disparities in mathematics. While the results were consistent across Study Three and Study Four, we would nevertheless suggest that working memory should not be entirely dismissed as a possible mechanism by which SES gaps could emerge – and that the way one operationalizes working memory may be crucial. In our studies, the working memory measure mostly indexed young children's visuospatial recall skills; this contrasts with the more complex working memory measures typically used with older children, which index the ability to manipulate and update information. Indeed, previous research has found small-medium SES differences in older children's working memory, using a working memory task with a manipulation element (Blakey et al., 2020; Lawson et al., 2018). Recent work has also identified working memory as a mediator of attainment gaps when a verbal measure is used (Waters et al., 2021). Therefore, it is possible that SES differences in the ability to process and manipulate information emerge over time and are more likely in the verbal domain, perhaps because SES shows gradients in language ability.

Somewhat unexpectedly, both Study Three and Study Four found that home mathematical activities did *not* relate to children's mathematical ability – and nor did they vary by SES. Therefore, SES gaps in early mathematical ability do not appear to arise as a function of differences in frequency of home mathematical activities. The absence of relation between frequency of home mathematical activities and mathematical ability is surprising, and worth further attention, not least because prior research on this topic has yielded contrasting results. The present findings are consistent with some prior studies (DeFlorio & Beliakoff, 2015; Missall et al., 2015; Zhou et al., 2006), but not others (Kleemans et al., 2012; Lefevre et al., 2009). One possible explanation could be the age of children: the current study was conducted with children prior to the start of formal education, in contrast to Lefevre et al. (2009) seminal study, which was conducted after children had begun formal education. It may be that the relation between home mathematical activities and mathematical ability is age-specific, with it emerging as children get older and are able to do more complex mathematical operations (Thompson et al., 2017). Another possible explanation for the diversity in findings might be the socioeconomic features of the samples tested. The majority of research into the frequency of home mathematical activities has been conducted with socioeconomically homogeneous samples. It is possible that the relation between frequency of home mathematical activities and mathematical abilities does not have the same strength across the SES spectrum, and is perhaps seen most strongly in higher-SES families. This would go some way towards explaining why no relation was found in study three (with a predominantly lower-SES sample) or in study four (with a diverse SES sample). This suggestion is wholly consistent with a meta-analysis showing that the positive relation between home mathematical activities and mathematical ability was larger in high-SES families than low-SES families (Dunst et al., 2017). The fact that both the present studies show this null relation, and that both use different home mathematical activities questionnaires, gives us confidence that in socioeconomically diverse samples, *frequency* of home mathematical activities does not influence mathematical ability prior to the start of formal education.

The absence of a SES gradient in frequency of home mathematical activities is noteworthy in its own right. Little previous research has directly explored this topic, and the few studies that do have tended to use socioeconomically homogeneous samples, or relatively basic measures of SES. The present research featured two commonly used measures of SES, and a diverse SES sample, and still found no relation between SES and frequency of home mathematical activities.

While this research did not find *frequency* of home mathematical activities to be a mechanism by which SES attainment gaps emerge, it is nevertheless conceivable that there is still a role to be played by home mathematical activities. It may be that a different picture will emerge when one considers not simply the *frequency* of mathematical activities in the home, but rather the *type*, *range* and *quality* of those activities. Indeed, language research has shown the importance of quality over quantity for a child's verbal ability (Hirsh-Pasek et al., 2015). It remains a possibility that type, range and quality of mathematical activities may influence mathematical development, and may themselves be differently influenced by SES. To test this possibility, studies need to go beyond questionnaire scales in order to gather richer data – for example, by using interviews and observations in the home, to fully capture the diversity of interactions and activities that may have mathematical components embedded (see Elliott et al., 2020). This suggestion is supported by research comparing questionnaire data with semi-structured interview data on home mathematical activities which found they did not correlate with one another (Mutaf Yıldız et al., 2018). Alternatively, it may be that the frequency of home mathematical activities predicts *growth* in mathematical ability, rather than a child's ability at a single time point, with early activities potentially providing a foundation to support the future acquisition of mathematical skills. Better understanding how the *type*, *range* and, *quality* of home mathematical abilities contribute to mathematical skills over time will be an important avenue for future research.

It is important to note limitations of the studies presented. The first and most important limitation concerns their cross-sectional nature. The mediation analysis conducted using the cross-sectional data is correlational, not causal. While the current studies provide a clear and robust account of factors that may be of interest, longitudinal research is needed to confirm the temporal ordering of these variables before conclusions can be drawn about causal mechanisms. For example, a bidirectional relation between the development of the executive functions and mathematical ability has been speculated (Schmitt et al., 2017). However, we note that a recent paper failed to replicate this finding in two large samples indicating that the causal relation does go executive functions to mathematical ability, not vice versa (Ellis et al., 2021). Existing longitudinal research has been particularly helpful in identifying predictors of later mathematical achievement. They have been valuable in demonstrating the importance of SES and early executive functions on later skills (Ahmed et al., 2018; Waters et al., 2021). However, of the longitudinal studies on this topic, many focus on older children who have started formal schooling, or do not look at mediators of attainment gaps directly. Instead, they elucidate predictors of later achievement and have extensive control variables (including verbal ability and SES) (Ahmed et al., 2018); or when they do examine attainment gaps, focus on executive functions (Waters et al., 2021). The predictors of attainment gaps, as this work has identified, are likely to be multi-factorial so it will be helpful for future work to examine how multiple predictors like executive functions, verbal ability, *and* the quality of activities in the home predict mathematical attainment gaps as they emerge early on and change over time.

Another limitation relates to the measurement of some of our variables. Firstly, our measure of working memory may have relied more on short-term memory and that may be why we found little relation between working memory and SES. As yet, there are no sensitive working memory tasks for three-year-olds that require both storage and processing. It would be beneficial for future research to develop such measures. Secondly, measuring the frequency of home mathematical activities may not capture the full range of activities parents do with their children, nor the quality of such activities. It would be helpful for future research to move beyond questionnaires, to measures that can capture the quality and breadth of home activities such as through observation. Thirdly, we focused on measuring factors that were most proximal to mathematical development. However, other more distal factors may also be important in explaining SES attainment gaps, including mathematical vocabulary. Mathematical vocabulary has been found to relate to preschoolers' early mathematical skills (King & Purpura, 2021), but less is known about its relation to SES. It would be fruitful to explore whether there is an SES gradient in children's mathematical vocabulary – and if so, whether mathematical vocabulary is a mediating factor to explain SES attainment gaps.

The present research is the first to directly investigate the specific factors that explain SES gaps in early ability in a diverse socioeconomic sample. In two studies, we find that SES attainment gaps for mathematical ability are explained by both verbal ability and inhibitory control. We find that frequency of home mathematical activities does not vary by SES, nor does it influence early mathematical ability. It may be fruitful for future work to focus on the *quality* of these activities above and beyond frequency. By providing a clearer understanding of how early SES gaps in mathematical ability arise, and by examining multiple key factors, these findings offer a vital first step towards designing longitudinal studies to elucidate on the long-term consequences of these early inequalities.

Chapter Five
A Systematic Review and Meta-Analysis of the Relation between Frequency of Home Mathematical Activities and Early Mathematical Ability

In recent years, there has been rapid growth in the number of studies exploring the relation between frequency of home mathematical activities and mathematical ability. However, the findings of studies have been inconsistent, with some studies finding a positive relation between frequency of home mathematical activities and mathematical ability, while others find no relation or even a negative relation. These disparate findings make it difficult to draw conclusions about the role of home mathematical activities for early mathematical ability. The current pre-registered meta-analysis synthesised the studies exploring the relation between frequency of home mathematical activities and mathematical ability in children aged seven years and under. The meta-analysis found an overall small positive relation between frequency of home mathematical activities and mathematical ability (r = .13). This relation was moderated by the type of mathematical ability measure used. The correlation was stronger when a composite mathematical measure or a number knowledge mathematical measures was used in comparison to a measure of magnitude estimation. No other mathematical ability measures were significant moderators, nor was study design, geographical location of data collection, or child age.

5.1. Introduction

Children's mathematical skills begin to develop in the preschool years, with disparities between their mathematical skills already visible on entry to formal education (Sirin, 2005). In order to support the development of children's mathematical skills and narrow disparities, it is crucial we identify factors that might be amenable to intervention early in development. Given that mathematical skills begin developing early and disparities can be seen even before children begin formal education, the home environment is a likely candidate to influence the development of early mathematical skills (Byrnes & Wasik, 2009). The home environment is where children spend a large proportion of their time before they start school and provides numerous opportunities for learning (see Bronfenbrenner, 1979; Vygotsky, 1978). There are many elements of the home environment which are likely to influence mathematical skills either indirectly, for example through parental scaffolding and resources (which are discussed at length in Chapter One), or more directly, such as through activities that have mathematical learning embedded, like home mathematical activities. Research exploring how much parents engage in home mathematical activities, and how important they are, is a relatively new field. The findings are already very varied with regards to how strong the relation is between home mathematical activities and children's mathematical skills. Therefore, a systematic review and meta-analysis is needed to examine these findings in more detail before determining whether home mathematical activities are a promising way to support children's mathematical development. Therefore, this chapter will be a systematic review and meta-analysis on the relation between frequency of home mathematical activities and early mathematical ability in early and early-mid development.

It is widely believed that home learning activities generally support the development of academic skills (Lehrl, et al., 2020). Indeed, it is well documented that the home literacy environment, including reading activities, is important for children's language and reading development (Dong et al., 2020). These findings have led to successful interventions to improve early literacy skills (Sénéchal & Young, 2008). However, until recently, relatively less attention has been paid to the role of home mathematical activities for the development of early mathematical skills (Lefevre et al., 2009; Skwarchuk et al., 2014). Over the past decade, there has been rapid growth in the publication of studies exploring the role of the home mathematical environment for mathematical skills. Within the literature, most studies exploring the home mathematical environment have focused on the *frequency* that parents engage in home mathematical activities with their children (Daucourt et al., 2021). The logic being that the more frequently parents engage in home mathematical activities with their children, the more opportunities there will be for children's mathematical skills to be nurtured. It would therefore follow that children from homes where parents engage in a higher frequency of mathematical activities will begin school with higher levels of mathematical ability than their peers who engage in a lower frequency of home mathematical activities. Frequency of home mathematical activities is commonly measured by asking parents to retrospectively indicate (e.g., within the past month) how frequently they engaged in a predetermined list of home mathematical activities using a five-point Likert scale which ranges from 'activities did not occur' to 'activity occurred almost daily' (e.g.,Cahoon et al., 2021; DeFlorio & Beliakoff, 2015; Lefevre et al., 2009; Skwarchuk et al., 2014; Sonnenschein et al., 2012). There is wide variation in the frequency of home mathematical activities parents report doing with their children (DeFlorio & Beliakoff, 2015; Lefevre et al., 2009). Thus, if home mathematical activities are important for early mathematical development, this may go some way in explaining variation seen in children's mathematical skills prior to the start of formal education.

A number of studies have found a relation between frequency of home mathematical activities and mathematical ability (Lefevre et al., 2009; Skwarchuk et al., 2014), however, the findings of studies have been inconsistent, with some studies finding no significant relation (Cahoon, et al., 2021; Missall et al., 2015; Zhou et al., 2006), and others finding a *negative* relation (Blevins-Knabe et al., 2000; Ciping et al., 2015). Indeed, the studies reported in Chapter Two and Chapter Four of this thesis did not find a significant relation between home mathematical activities and early mathematical ability. These inconsistent findings between studies make it difficult to draw firm conclusions. This is a problem because of the studies that *do* find a positive relation, they often call on future research to develop interventions on home mathematical activities to support children's mathematical skills (Skwarchuk, 2009). However, this may be premature if the relation only exists weakly, or can be explained by other unmeasured variables. Before any recommendations can be made to caregivers we need to determine firstly if there is a genuine relation, and then further explore what activities are most impactful.

Inconsistencies in the results in the literature exist not only between studies but also *within* studies. For example, Lefevre et al.'s (2009) seminal study is widely reported as one of the first key studies to find a relation between frequency home mathematical activities and mathematical ability (e.g., DeFlorio & Beliakoff, 2015; Kleemans et al., 2012; Sonnenschein et al., 2012). However, Lefevre et al.'s (2009) study has disparate findings within the study. The study reports multiple relations between home mathematical activities and mathematical ability. This is because firstly, the study used principal component analysis to divide the activities in their home mathematical activities scale into four categories: number skills, number books, games, and applications. Secondly, the study took two measures of mathematical ability: a mathematical knowledge measure (i.e., measured numeration, addition, and subtraction ability) and a mathematical fluency measure (i.e., accuracy and medium latency of correct responses of single-digit addition problems). Out of the eight relations reported between home mathematical activities (number skills, number books, games, applications) and mathematical ability (knowledge, fluency), only the relation between the home mathematical activities games factor and both mathematical knowledge and mathematical fluency showed a significant positive relation. Markedly, the relation between number books and mathematical fluency was a significant negative relation. The five other relations reported between home mathematical activities and mathematical ability were not significant. There are a number of other studies which suffer from similar internal inconsistencies in results (e.g., Ciping et al., 2015; del Río et al., 2017; Huang et al., 2017; Ramani et al., 2015) and these inconsistencies make it difficult to draw conclusions about the true influence that frequency of home mathematical activities has on early mathematical ability.

Understanding the role of home mathematical activities for early mathematical development is important as there is reason to believe they may be malleable to change, thus if there is a genuine relation this offers a possible target for intervention. Notably, home literacy activity research suggests that parent-child home literacy activities are malleable and can result in academic benefits for children (Sénéchal & Young, 2008). Therefore, it may be possible to also intervene and increase the quantity and quality of home mathematical activities using similar approaches. It is possible to target home learning activities through two prongs: firstly, parent education to equip parents with the understanding that home learning activities are important, the knowledge of the types of mathematical activities to engage in, and how to engage in them with their children (National Literacy Trust, 2018); and secondly, by giving parents the resources to engage in home activities, for example books (National Literacy Trust, 2018). Within literacy interventions, both approaches together have been found to be effective (de Bondt et al., 2020; National Literacy Trust, 2018; Save the Children, 2016). However, before interventions can be developed, it is crucial that we establish whether home mathematical activities are in fact as important to mathematical development as literacy activities have been found to be important to early literacy development.

There are several factors that may go some way in explaining disparities in the relation between frequency of home mathematical activities and mathematical ability which could include demographic features of the sample and study characteristics. In particular, demographic factors such as children's age, socioeconomic make-up of the sample, and geographical location of data collection may influence the strength of the relation. Study characteristics are likely to also be important in explaining disparities, such as whether the study design was concurrent or longitudinal, as well as the measures used and how they were analysed, and whether studies were adequately powered to detect a significant effect. Each of these will be discussed in turn below.

Firstly, the age of children in a study may influence the relation between home mathematical activities and mathematical ability. It is likely that both the frequency and types of home mathematical activities parents do with their children changes over time. Indeed, DeFlorio & Beliakoff (2015) found differences in the types of activities parents engaged in more frequently when comparing children over one year, with a mean age 3.5 years to 4.5 years. Younger children were more likely to engage in block games whereas, older children were more likely to use maths workbooks. It is conceivable that home mathematical activities have a larger influence on mathematical development in early childhood as this is when children will primarily be given mathematical learning input because they cannot yet scaffold their own learning independently and may not yet be guided by their school.

Secondly, it is possible that the socioeconomic makeup of the study sample influences whether a relation is found between frequency of home mathematical activities and mathematical ability. Elliott & Bachman (2018) suggest that home mathematical activities may be a mechanism by which socioeconomic disparities in early mathematical ability arise. Indeed, a previous meta-analysis looking at the influence of home and family numeracy learning experiences on early mathematical skills found that a positive relation between these learning experiences and mathematical ability was larger in high-SES families than low-SES families (Dunst et al., 2017). It is possible that this is due to higher-SES parents having more resources and knowledge to engage in home mathematical learning. Indeed, we know that home learning resources do vary by SES, with lower-SES parents having fewer learning resources than higher-SES parents (Daucourt et al., 2021). It is therefore possible that the disparate results are, in part, due to the differing socioeconomic makeup of study samples.

Thirdly, researchers in numerous countries have explored the role of frequency of home mathematical activities on mathematical ability (e.g., LeFevre et al., 2010; Pan et al., 2018; Soto-Calvo et al., 2020). It is conceivable that the geographical location in which studies are conducted may influence the relation found between home mathematical activities and mathematical ability. For example, parents in countries who have access to a high level of support through wide ranging early years provisions may support parents and equip them with the knowledge to implement home learning activities, compared to parents who live in countries who have less access to such support (Bertram et al., 2016; OECD, 2019). Alternatively, in countries where children have access to preschool from a younger age, the role of the home environment for early educational development may be lower than in countries where children enter preschool at a later age. It is also possible that the emphasis placed on the importance of mathematical learning in the early years differs across cultures, both in whether activities are seen as important but also which home mathematical activities are important. To support this point, cross-country comparisons between Greece and Canada found that Canadian parents reported a higher frequency of making/sorting collections and using computer software, whereas Greek parents reported higher frequency of playing board or card games (LeFevre et al., 2010). To this end, it is possible that certain home mathematical activities are more beneficial than others for the development of early mathematical skills, and thus activities more common in one country may be more supportive of mathematical skill development than other activities more common in other countries.

Fourthly, whether a study explored the relation between frequency of home mathematical activities at a single time point or multiple time points may influence the relation found between home mathematical activities and mathematical ability. It is plausible that home mathematical activities lay important foundations for later mathematical skill development, providing building blocks for more advanced mathematical skills to be built upon. Or in other words, home mathematical activities predict *growth* in skills over time. If this were true, we would expect studies using a longitudinal design to be more likely to find a relation between home mathematical activities and mathematical ability than studies conducted at a single time point.

Fifthly, differences in the way mathematical ability is measured, both between- and within- studies, may explain some disparities in findings. Some studies measure mathematical ability using a composite measure, where a variety of mathematical skills are measured, and performance is combined to give an overall mathematical ability score (e.g., Cahoon et al., 2021; Lefevre et al., 2009; Wei et al., 2020). While other studies measure individual mathematical skills, such as counting, cardinality, numerical magnitude, or spatial skills e.g., (Cheung et al., 2020; Cheung et al., 2018; Soto-Calvo et al., 2020) and explore the relation between home mathematical activities and these specific mathematical skills (see Chapter One for an overview of the development of these mathematical skills). Furthermore, some studies use a standardised measure of mathematical skills that taps many different aspects of mathematical ability. It is likely that not all home mathematical activities have equal influence on all mathematical skills. For example, one might expect a child who does lots of counting activities at home to have higher counting skills, but not necessarily spatial skills. Moreover, it is possible that composite measures eliminate the nuance necessary to find relations between mathematical activities and mathematical ability. For example, it may be that the home mathematical activities asked about are more likely to relate to certain mathematical skills (e.g., counting) than others (e.g., shape recognition). Using individual measures of mathematical ability would enable this identification, however, if a composite measure of mathematical ability, measuring a range of skills (with some influenced by activities and others not), is used then this may not show a relation. Therefore, the type of mathematical skills measured in studies looking at the relation between home mathematical activities and mathematical ability and the way they are combined or not, may, in part, explain the disparate findings.

Sixthly, many studies which have found a significant positive relation between home mathematical activities and mathematical ability, have found a relation that is small in magnitude (e.g., Lefevre et al., 2009; Missall et al., 2015; Soto-Calvo et al., 2020). This raises questions around whether studies which have not found a significant relation were simply not adequately powered to do so. A meta-analysis enables an effect to be detected across multiple studies, where individual studies may not have the power to detect a significant effect (Jackson & Turner, 2017) which underscores why this meta-analysis is needed.

There have been several previous attempts to synthesise the home mathematical environment literature. There have been two previous attempts to *qualitatively* synthesise the literature on frequency of home mathematical activities and mathematical ability. The first, Bennett (2017) was a systematic review within a thesis. This systematic review highlights that there are a wide range of findings, from significant positive relations, no relations, to significant negative relations between home mathematical activities and mathematical ability. Bennett (2017) offers plausible explanations for why findings vary, including the age of children, the country of data collection, the different scales used to measure frequency of home mathematical activities, as well as the different measures used to measure mathematical ability. More recently, Mutaf-Yıldız et al. (2020) published a systematic review on the relation between frequency of home mathematical activities and mathematical ability, which again highlighted the disparate findings. They conclude that the measures implemented as well as sample characteristics may, in part, be responsible for inconsistent findings. However, until recently there has not been a quantitative synthesis of studies exploring the relation been frequency of home mathematical activities and mathematical ability. This has limited our ability to draw wider conclusions on the research area.

Looking at the home mathematical *environment* more broadly (not specifically home mathematical activities), there have been two meta-analyses. Dunst et al. (2017) published a meta-analysis of the relation between home and family numeracy learning experiences and mathematical ability in a book review. The meta-analytic sample consisted of 13 samples with children aged between three- and seven- years, finding an overall effect size of .46 for relation between home and family numeracy learning experiences and mathematical ability. However, this meta-analysis did not include key studies such as Lefevre et al.'s (2009) seminal study, raising questions about the rigor in their search strategy to include all eligible literature. Furthermore, the meta-analysis included studies which had literacy questions with the activitiy questionnaire. Additionally, since 2017 a number of studies exploring the home mathematical environment have been published. Recently (while I was conducting my meta-analysis), a meta-analysis by Daucourt et al. (2021) explored studies looking at the wider home mathematical environment. The meta-analysis found a small positive relation, across 65 studies, between the home mathematical environment and mathematical ability (r = .13). The majority of the studies which met the inclusion criteria for this meta-analysis looked at the *frequency* parents engage in home mathematical activities. However, it is important to note that this was not the sole focus of the meta-analysis and that the meta-analysis included studies looking at number talk, and parent attitudes and beliefs about mathematics. Therefore, we are unable to conclude whether *frequency* of home mathematical activities specifically has an overall positive relation with home mathematical activities. Furthermore, the meta-analysis had a wide age span, focusing on children between the ages of three- to fourteen- years-old making it difficult to draw conclusions about whether the home mathematical environment is important specifically for younger children. Interestingly, even though this review was published very recently, the search was conducted at the beginning of 2018, and since the research field is growing rapidly this review did not include at least 19 recent studies that have become available since.

In conclusion, the incongruent results both between studies and within studies make it difficult to determine the influence that home mathematical activities have on early mathematical ability. While a recent meta-analysis by Daucourt et al., (2021) indicates that there is a small positive relation between the home mathematical environment and mathematical ability, the review focuses on the wider home mathematical environment, limiting the conclusions that can be drawn about the specific role of frequency of home mathematical activities, and their relation to early mathematical ability. Furthermore, this meta-analysis included studies conducted across a large age range, limiting the conclusions we can draw about the home mathematical environment for the development of *early* mathematical skills. Until we are able to gain a better understanding of whether home mathematical activities do in fact influence early mathematical ability, we will not be able to recommend home mathematical activities as a target for intervention to support early mathematical development and potentially narrow inequalities seen in early mathematical skills.

The aim of the current meta-analysis is to provide a quantitative synthesis of existing research which has explored the relation between frequency of home maths activities and early maths ability in young children. There are four research questions: firstly, is there a relation between frequency of home maths activities and maths ability? Secondly, how strong is this relation across studies? Thirdly, are the differing effect sizes a result of random variability or is the literature heterogeneous? Fourthly, can the heterogeneity be attributed to the following moderators: (i) age of children, (ii) SES (iii) study design (concurrent vs. longitudinal), (iv) type of mathematical ability measure, (v) the country of data collection?

5.2. Method

The current meta-analysis was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The meta-analysis was preregistered (DOI 10.17605/OSF.IO/6HUCW).

5.2.1. Study Selection, Data Extraction, and Coding

5.2.1.1. Literature Search

The initial literature search was conducted in June 2018 using three individual databases: Scopus, Web of Science, and PsycINFO. The search was updated on these databases in April 2021. An additional database, Proquest, was also searched in May 2021 for theses and dissertations. The following search terms were used:

("Home learning environment*" OR "Home numeracy environment*" OR "Home math* environment*" OR "Home learning" OR "Home math* learning" OR "Home numeracy learning" OR "Home learning activit*" OR "Home numeracy activit*" OR "Home math* activit*" OR "Home experience*" OR "Home math* experience*" OR "Home numeracy experience*")

AND ("Math*" OR "Numeracy*" OR "Arithmetic*" OR "Number*")

AND ("Child*" OR "Toddler" OR "Infan*" OR "Pre-school" OR "Pre school" OR "Preschool*" OR "Kindergarten" OR "Pre-kindergarten" OR "Pre kindergarten")

The database search results were exported to EndNote (The EndNote Team, 2013). Reference lists of the final sample of articles were searched to identify relevant articles which had not been located via the database searches, resulting in the inclusion of one further study. In addition, in May 2021 an attempt to include unpublished data was made by contacting prominent authors in the field: Abbie Cahoon, Alexa Ellis, Bert De Smedt, Bert Reynvoet, Camilla Gilmore, David Purpura, Fiona Simmons, Frank Niklas, Jo-Anne LeFevre, Tom Gallagher-Mitchell, and Victoria Simms, as well as emailing relevant mailing lists (cogdevsoc, dev-europe, and mathlink). This resulted in a total of 12 unpublished samples being including in the final meta-analysis.

5.2.1.2. Inclusion Criteria

All studies included in the meta-analysis were required to meet the following criteria:

(a) Age: children with a mean age of up to and including 7 years.

(b) Type of home mathematical environment scale: Frequency of home mathematical activities measured using a multi-item (i.e., more than one item) questionnaire to measure frequency of home mathematical activities.

(c) Measure of maths ability: A direct measure of child mathematical ability included in the study (i.e., not parent or teacher rated).

(d) Child: Children must not have known developmental disorders or special educational needs.

(e) Language: Written in English.

(f) Relation: Study must look at the relation between frequency of home maths activities and maths ability.

It is important to note that the final inclusion criteria implemented differed slightly from the preregistered inclusion criteria in that the preregistered criteria stated that only published studies would be included. However, to limit publication bias, we decided it was important to expand our inclusion criteria to PhD theses and grey literature.

5.2.1.3. Study Selection

A flow chart depicting the search process and exclusion of studies is displayed in Figure 5.1. Duplicates were excluded in EndNote based on Bramer et al.'s (2016) procedure. All non-duplicate studies were reviewed against the inclusion criteria. Firstly, article titles were screened. During title screening, studies that were not within the broad topic area were excluded. Secondly, abstracts were screened. During abstract screening studies which clearly did not meet the inclusion criteria were excluded. The initial search resulted in 238 papers being retrieved for full text screening, while the updated search resulted in an additional 71 papers being retrieved for full text screening. During full-text screening, articles were reviewed against the full inclusion criteria. Only articles which met the full inclusion criteria were included in the final meta-analytic sample. A total of 73 independent samples met the inclusion criteria and made up the final meta-analytic sample.

To avoid the biasing effect of including a single data set more than once (Borenstein et al., 2009), where both unpublished and published studies were available, only the published record was included. If a study included multiple independent samples, these were included and treated as separate studies (Borenstein et al., 2009).

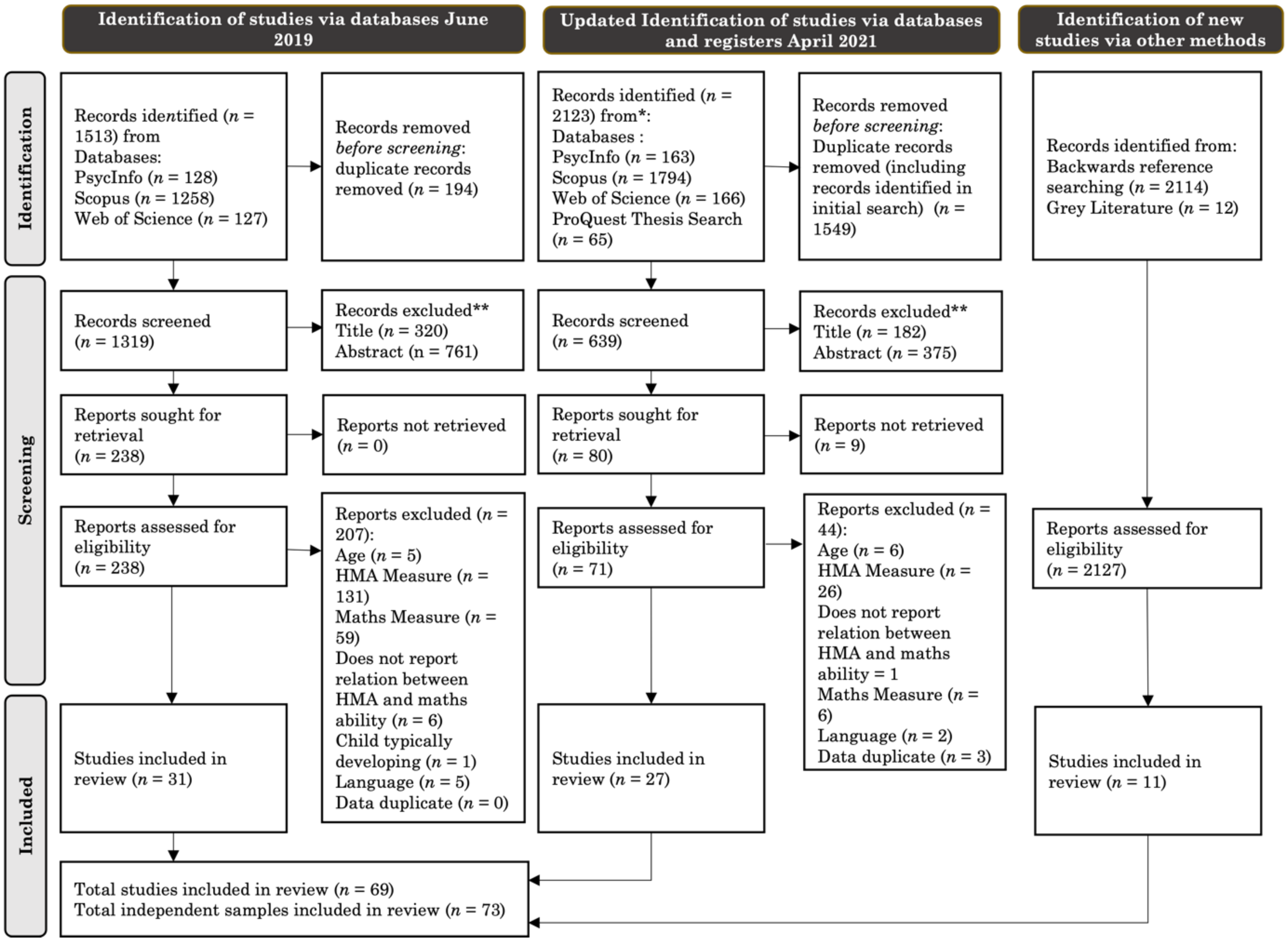


Figure 5.1 PRISMA diagram detailing the records identified, screened, and included in the meta-analysis based on the search strategy.

5.2.2. Data Extraction

Four coders underwent coding practice, and the papers were divided between the coders for data extraction. The following information was extracted from all studies which met the inclusion criteria: (a) bibliographic information (e.g., author, title, year, publication status), (b) study design (i.e., concurrent or longitudinal), (c) sample descriptors (e.g., age, socioeconomic information, country of data collection), (d) outcome details (i.e. type of mathematical ability measure), (e) outcome data (i.e., sample size; zero-order correlation coefficient).

If a study met the inclusion criteria but did not report zero-order correlations between frequency of home mathematical activities and mathematical ability, the corresponding author was contacted via email to procure the data. If authors did not respond to the initial request, after two weeks had passed, authors were sent a follow up request asking them to provide the data within the next week. If authors did not respond to the second request, the study was removed from the meta-analysis (a total of seven studies were removed).

5.2.2.1. Moderators

Table 5.1 provides a complete list of moderator variables examined. We intended to look at SES as a moderator, however, inadequate reporting of socioeconomic information in the majority of studies meant that socioeconomic status was not coded for moderator analysis. Inadequate coding included not reporting SES at all (e,g., Huang et al., 2017), or studies arbitrarily coding SES into 'high' and 'low' categories, based on the SES distribution of their sample, rather than to reflect the SES of the population (e.g., DeFlorio & Beliakoff, 2015; Lefevre et al., 2009). Many studies did report level of education, however, it is difficult to compare level of education across countries. Geographical location of data collection was examined by grouping studies by the country of data collection. For many countries, there were not enough countries in a geographical location to group them as it is recommended to have at least four, but preferably 10 studies per category (see Fu et al., 2010). Therefore, we grouped studies in three geographic locations: North America, Europe (excluding the UK), and the UK. For type of mathematical ability measure, spatial ability was also coded however, only three samples reported spatial ability, which was not enough to explore spatial ability as a moderator (see Fu et al., 2010).

Table 5.1 Moderator Variable Description

Variable	Description	Coding
Age of Children	This details children's age in months	Continuous Measure
Geographical Location of Data Collection	This details the country in which data was collected	1 = North America 2 = Europe (excluding the UK) 3 = United Kingdom
Study Design	Details whether the study collected outcome data at a single time point or multiple time points	1 = Concurrent 2 = Longitudinal
Type of Mathematical Ability Measure	This details the type of mathematical ability outcome measure taken.	1 = Composite 2 = Counting 3 = Number knowledge 4 = Magnitude Estimation 5 = Operations 6 = Spatial Skills[a] 7 = Non-Symbolic Skills
Publication Status	Details whether the study was located in journal or from another location (e.g., thesis/ dissertation/ unpublished data)	1 = Published 2 = Not published

Note. [a] not explored as a moderator as too few studies reported using this measure.

5.2.3. Analyses

5.2.3.1. Effect Size Calculation

The final data was imported into R (version 4.1.2). The majority of studies included used correlational design that report Pearson correlations, therefore zero-order coefficient was used to calculate effect size between frequency of home mathematical activities and mathematical ability. Some studies used experimental design (e.g., Niklas et al., 2016). In these cases, only baseline data was included. Fisher's Z-transformed correlations and variance of each effect size were calculated using the correlation coefficients and sample size with the function 'escalc()' in the package metafor (Viechtbauer, 2010). All analyses were performed with the Fisher's Z-transformed effect size, and were then converted back to r for reporting.

5.2.3.2. Variability in Effect Sizes Across Studies

The average weighted correlation between frequency of home mathematical activities and mathematical ability was estimated using a random effects model. A random-effects model was chosen as the true effect size was expected to vary across studies, whereas a fixed-effects model would assume that all studies shared a true effect size (Borenstein et al., 2009). We expected variation in effect size to vary across studies because the studies were conducted in different countries, with children of different ages, using different home mathematical activity scales, and different measures of mathematical ability.

5.2.3.3. Heterogeneity of effect sizes

Heterogeneity of effect sizes was measured using a *Q* test which indicates whether heterogeneity of effect size is present in the meta-analytic sample. I^2 was then calculated to quantify the proportion of variance in effect size due to heterogeneity (Higgins & Thompson, 2002). Heterogeneity supports the use of a random-effects model, whereas homogeneity would support the use of a fixed-effects model.

5.2.3.4. Accounting for Dependent Effect Sizes

Eighty percent of studies included in the meta-analysis reported more than one effect size. Therefore, to allow for estimating unbiased standard errors, a three-level meta-analysis clustering effect sizes at both study-level and observation-level was run. Study-level and observation-level estimates enable the identification of how much variance is a result of between-study differences (i.e., how the relations differ across studies), compared to within-study differences (i.e., how the relations differ within a single study).

5.2.3.5. Analysing Variability in Effect Sizes

To establish whether the hypothesised moderators explained variance in effect sizes, multiple models controlling for between- and within- study variance were tested. Omnibus tests based on the *F*-distribution were conducted for each moderator variable. This indicates whether the subgroup effect sizes significantly differ from one another, thus establishing a moderator. Random-effects multi-level models for each moderator sub-group were conducted to determine the overall effect sizes for each subgroup within a moderator.

5.2.3.6. Evaluation of Publication Bias

Publication bias refers to the phenomenon that studies which report significant findings ($p < .05$) are more likely to be published (Rosenthal, 1979). Publication bias can affect the validity of a meta-analysis, resulting in an over- or under-estimation of the true population effect size (Lin & Chu, 2018). Publication bias was assessed using visual and statistical techniques to indicate whether studies with significant findings were more likely to be published than findings which were not significant.

P-curve analysis was conducted to indicate whether there was evidence of *p*-hacking. *P*-hacking refers to the phenomenon where researchers engage in practices which make their results more likely to be statistically significant. This can include the way data is collected, analysed, and selected for reporting (Head et al., 2015). *P*-curve analysis calculates pp-values, which are the probability of obtaining each *p*-value if there was no significant effect. To test whether a *p*-curve is significantly skewed, *pp*-values were added together to create a $\chi 2$ value to test the significance of the *p*-curve skew. A flat *p*-curve signifies equal probability of observing *p*-values; a right-skewed *p*-curve indicates a true effect, and thus a low chance of publication bias. A *p*-curve with left skew shows that the probability of high *p*-values is greater than the probability of low p-values, and thus demonstrates that there is evidence of *p*-hacking. *P*-curve analysis was conducted using the *p*-curve application available at: http://www.p-curve.com/app4/.

Funnel plot was used to visually assess whether there is publication bias (Light & Pillemer, 1984). Funnel plots show the relation between effect size and standard errors. Effect sizes which are symmetrically distributed around the vertical line indicate no publication bias, whereas effect sizes which are not symmetrically distributed around the vertical line would indicate potential publication bias.

Fail safe N was calculated using the Rosenthal method (Rosenthal, 1979). This calculated how many non-significant effect sizes would be required to reduce the combined significance level. Specifically, alphas of p <.05 and p < .01 were tested

5.3. Results

5.3.1. Final Article Sample

The final article sample for the meta-analysis consisted of 351 effect sizes from 73 independent samples, reported in 69 articles. Each study contributed between 1 and 24 effect sizes (median = 3). A summary of study data included can be found in Appendix 3.

5.3.2. Overall Average Weighted Correlation between Home Mathematical Activities and Mathematical Ability

The three-level meta-analytic model revealed a small significant positive correlation between home mathematical activities and mathematical ability of $r = 0.13$ (95% CI: [0.10, 0.16], $p < .001$). There was significant variance in the overall average effect sizes ($Q[350]$ = 1293.43, $p < .001$, $I^2_{Total} =$ 81.36%), thus supporting the decision to use a random-effects model that assumes between-sample variance. Approximately 80% of variance between frequency of home mathematical activities and mathematical ability was not due to sampling error. The estimated variance components were $\tau^2_{Level\ 3} = 0.009$ and $\tau^2_{Level\ 2} = 0.007$, with 46% of total variation being attributed to between-study variation ($I^2_{\text{Level 3}}$), and 35% of total variation was attributed to within-study variation ($I^2_{\text{Level 2}}$). A three-level model was compared to a two-level model where level 3 heterogeneity was constrained to zero. A three-level model provided a significantly better fit compared to a two-level model ($\chi^2_1 = 76.73$; $p < 0.001$). This supports a three-level meta-analysis. Figure 5.2 shows a forest plot with the composite effect size per study.

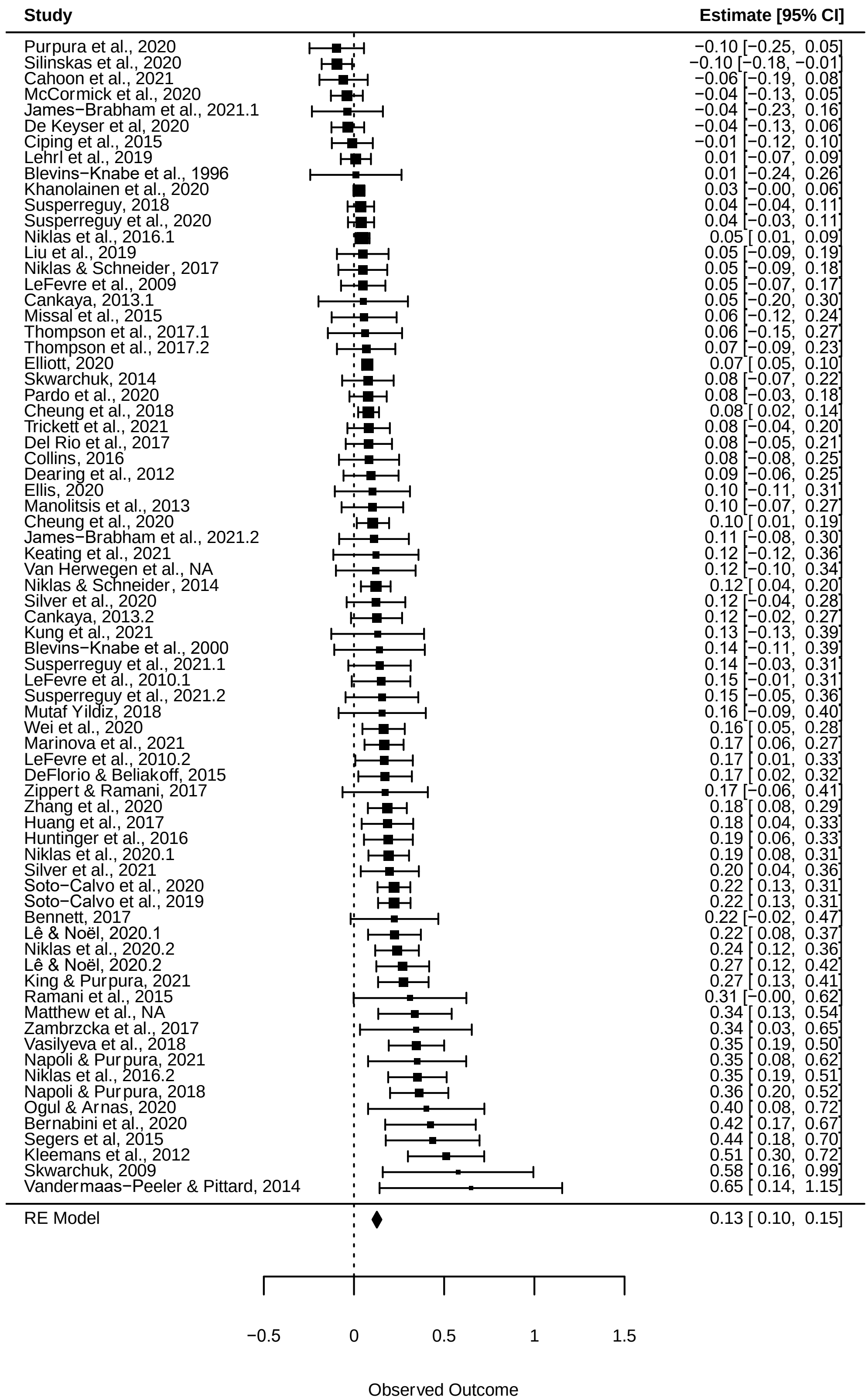


Figure 5.2 Forest plot depicting average effect size and 95% confidence intervals for each independent sample included in the meta-analysis. Note that this shows average effect size, where if a study contained more than one effect size, a composite variable with average effect size was created. For the multi-level meta-analysis reported, individual effect sizes and not composite effect sizes are used.

5.3.3. Moderators of the Effect

Multiple moderator analyses were conducted to determine whether study design (i.e., concurrent vs. longitudinal), geographical area of data collection, child age, and type of mathematical ability measure used significantly contributed to effect size heterogeneity. Each potential moderator was assessed individually. All moderators were entered as categorical variables, except for age which was entered as s continuous variable. The overall effect size for each subgroup is reported in Table 5.2.

Table 5.2 Summary of Effect Sizes for Subgroup Analyses

Moderator	Subgroup	*r*	95% CI	*n*	*k*
Geographical Location	North America	.14	0.10, 0.19	112	30
	Central Europe	.12	0.06, 0.18	53	16
	UK	.11	0.02, 0.19	45	8
Study Design	Concurrent	.15	0.12, 0.19	202	52
	Longitudinal	.10	-0.11, 0.00	149	21
Type of Mathematical Ability Measure	Composite	.15	0.11, 0.18	179	56
	Counting	.10	0.04, 0.16	17	13
	Numerical Knowledge	.15	0.11, 0.20	58	17
	Magnitude Estimate	.07	0.01, 0.12	27	11
	Operations	.12	0.07, 0.17	46	14
	Non-Symbolic	.09	0.03, 0.15	19	11

Note. *r* = Pearson's *r*, CI = Confidence Interval, *n* = number of effect sizes, *k* = number of independent samples.

5.3.3.1. Moderation Effects of Age (k=73)

The omnibus test with age was not significant, $F(1{,}348) = 0.522$, $p = .470$, $\tau^2_{Level\ 2} = 0.01$, $\tau^2_{Level3} = 0.01$, n=350 , $I^2 = 81.32\%$, indicating that the overall relation between frequency of home mathematical activities and mathematical ability was not significantly moderated by age.

5.3.3.2. Moderation Effects of Geographical Location of Data Collection (k=54)

The omnibus test with geographical location of data collection was not significant, (F(2, 207) = 0.34, $p = .710$, $\tau^2_{Level\ 2} = 0.01$, $\tau^2_{Level3} = 0.01$, n=210, $I^2 = 83.22\%$), indicating that the overall relation between frequency of home mathematical activities and mathematical ability was not significantly moderated by country.

5.3.3.3. Moderation Effects of Study Design (k=73)

The omnibus test with study design was not significant, (F[1, 349] = 3.71, $p = .055$, $\tau^2_{Level\ 2} = 0.01$, $\tau^2_{Level3} = 0.01$, n=351, $I^2 = 80.88\%$), indicating that the overall relation between frequency of home mathematical activities and mathematical ability was not significantly moderated by study design (i.e., whether the study was longitudinal or concurrent).

5.3.3.4. Moderation Effects of Mathematical Ability Measure (k=73)

The omnibus test with mathematical ability measure was significant ($F(5, 340) = 2.67$, $p = .022$, $\tau^2_{Level\ 2} = 0.01$, $\tau^2_{Level3} = 0.01$, n=346, $I^2 = 80.68\%$), indicating that at least one of the subgroups within the home mathematical ability measure was statistically significantly different from at least one of the other subgroups. Therefore, this was followed up with pairwise comparisons which are reported in Table 5.3. Pairwise comparisons revealed that the average weighted correlation between frequency of home mathematical activities and a composite mathematical measure was significantly higher than a magnitude estimation measure (b = -0.08, t[340] = -2.94, $p < .01$). They also revealed that the average weighted correlation between frequency of home mathematical activities and number knowledge was significantly higher than magnitude estimation (b = -0.09, t[340] = -2.82, $p < .01$). However, the heterogeneity was still significant ($p < .001$). No other mathematical ability measures significantly differed from one another in their relation to home mathematical activities.

Table 5.3 Pairwise Comparisons of Type of Mathematical Ability Measure

	beta	**95% CI**	***k***	***n***
Composite vs. counting	-0.05	-0.11, 0.02	64	196
Composite vs. number knowledge	0.01	-0.04, 0.06	69	237
Composite vs. magnitude estimation	**-0.08****	**-0.13, -0.03**	**61**	**206**
Composite vs. operation	-0.02	-0.08, 0.03	67	225
Composite vs. non-symbolic	-0.05	-0.11, 0.01	62	198
Counting vs. number knowledge	0.05	-0.01, 0.12	18	75
Counting vs. magnitude estimation	-0.03	-0.11, 0.04	21	44
Counting vs. operations	0.02	-0.05, 0.10	21	63
Counting vs. non symbolic	-0.01	-0.09, 0.08	20	36
Number knowledge vs. magnitude estimation	**-0.09****	**-0.15, -0.04**	**21**	**85**
Number knowledge vs. operations	-0.03	-0.09, 0.03	23	104
Number knowledge vs. non-symbolic	-0.06	-0.13, 0.01	22	77
Magnitude estimation vs. operations	0.06	-0.01, 0.12	20	73
Magnitude estimation vs. non-symbolic	0.03	-0.04, 0.09	17	46
Operations vs non-symbolic	-0.03	-0.10, 0.05	21	65

Note. CI = Confidence Interval, k = number of independent samples, n = number of effect sizes. Statistically significant comparisons are displayed in bold, **$p < .01$.

5.3.4. Publication Bias

Type of publication was explored as a moderator to see whether effect sizes significantly differed across samples which were published vs. unpublished (including grey literature and dissertations/theses). The omnibus test with publication type was not significant, ($F(1, 349) = 3.71$, $p = .055$, $\tau^2_{Level\ 2} = 0.01$, $\tau^2_{Level3} = 0.01$, n=351, k =73 , $I^2 = 80.89\%$), indicating that the overall relation between frequency of home mathematical activities and mathematical ability was not significantly moderated by publication type. This suggests that published studies are not more likely to report a significant relation between frequency of home mathematical activities and mathematical ability when compared to unpublished studies.

The *p*-curve analysis plot is displayed in Figure 5.3. The continuous *p*-curve analysis indicated both the full (Z = -.20.31, p < .001) and half (Z = -18.02, p < .001) *p*-curve test indicate significant right skew. This suggests that it is not likely the results are caused by publication bias. Furthermore, the full *p*-curve, half *p*-curve, and binomial 33% power test, were non-significant (full: Z = 10.64, p > .999; half: Z = 19.56, p > .999; binomial: p > .999). Together, these results suggest that there is no evidence of *p*-hacking in the current meta-analytic sample.

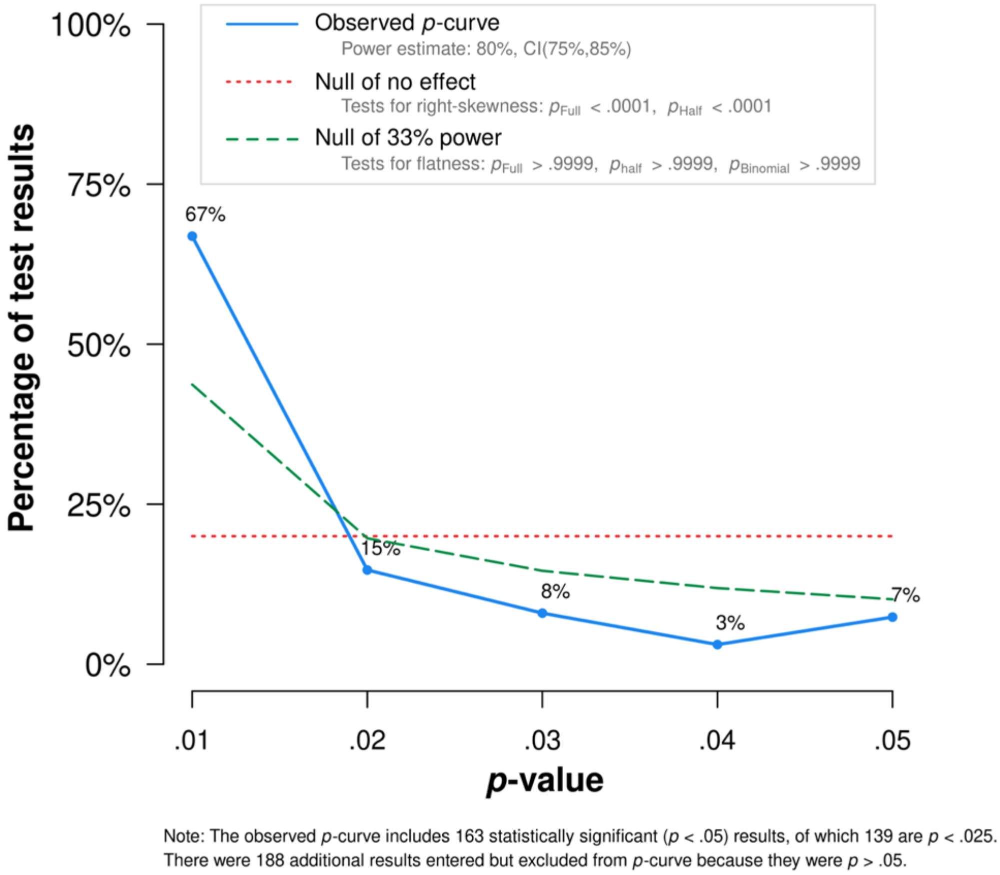


Figure 5.3 *P*-curve analysis results which indicate significant right skew, with non-significant result for the full- and half- p-curve tests. This indicates no substantial evidence of *p*-hacking in the meta-analytic sample.

The funnel plot, displayed in Figure 5.4, depicts the effect sizes for the meta-analytic sample relative to their standard errors (Sterne & Egger, 2001). Effect sizes are distributed around the vertical line and thus do not indicate publication bias.

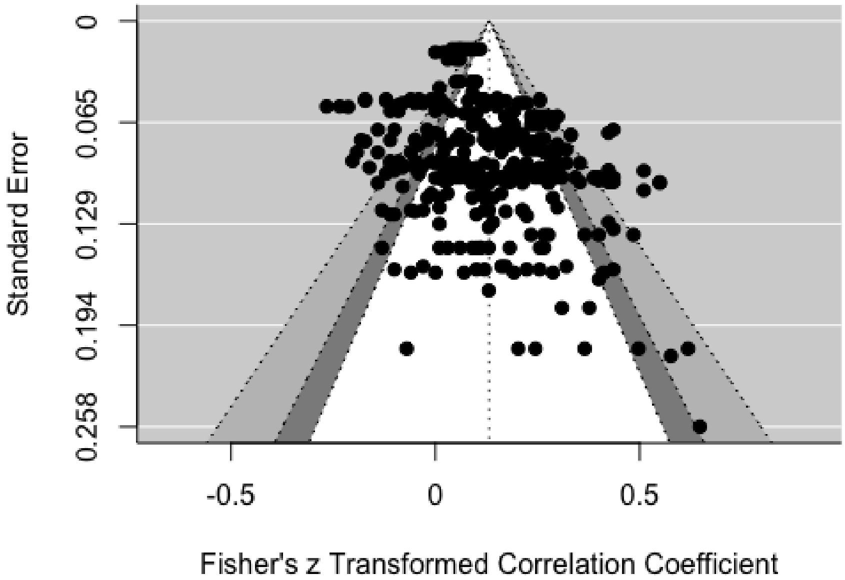


Figure 5.4 Funnel plot of the multilevel correlated effects meta-analysis. Confidence intervals on the 90th (white), 95th (dark grey), and 99th (light grey) percentiles.

5.3.5. Sensitivity Analysis

The Fail-safe *N* test using the Rosenthal approach revealed an additional 53,204 effect sizes with a relation of zero would be needed to increase the *p* value to >.01. An additional 106,774 effect sizes with a relation of zero would be needed to increase the *p* value to >.05. The large Fail-safe *N* suggests it is unlikely the results were susceptible to publication bias.

5.4. Discussion

The aim of the current meta-analysis was to provide a quantitative synthesis of existing research which has explored the relation between frequency of home mathematical activities and early mathematical ability. The results of the meta-analysis indicate that there is an overall positive relation between frequency of home mathematical activities and mathematical ability. However, the strength of this relation is small (r = .13) which may go some way in explaining why there has been such a debate in the field regarding the size of the effect. The studies were heterogenous meaning that the effect sizes were not a result of random error and truly differed. The type of mathematical ability measure used did, in part, significantly explain heterogeneity in effect size, with composite mathematical measures and the number knowledge measures explaining significantly more variance between home mathematical activities and mathematical ability than magnitude estimation measures. All other comparisons between mathematical ability measures were not significant. Children's age, study design, and geographical location of data collection did not significantly explain heterogeneity in effect size. It is possible that other factors, not explored in this meta-analysis, may explain this variance. One example is SES, which unfortunately due to studies not reporting this information in their samples hampered our efforts to explore this.

This meta-analysis provides the first synthesis of results on the relation between frequency of home mathematical activities and mathematical ability in young children, indicating that there is an overall positive relation between frequency of home mathematical activities and mathematical ability. This brings much needed clarity to the research area as it suggests that children who do a higher frequency of home mathematical activities with their parents tend to have a higher mathematical ability than their peers who are engaged in a lower frequency of home mathematical activities. This is similar to the home literacy environment literature which has found that frequency of home literacy activities is positively related to vocabulary and reading (Dong et al., 2020), and has led to successful home literacy activity interventions (Sénéchal & Young, 2008). However, the magnitude of effect of literacy activities was considerably larger (.65) compared to the size of effect found for home mathematical activities in the current meta-analysis (.13). Nevertheless, an overall positive relation between frequency of home mathematical activities and mathematical abilities indicates that frequency of home mathematical activities is a plausible target for interventions to improve early mathematical skills.

It is important to emphasise that the relation between frequency of home mathematical activities and mathematical ability is small (r = .13). The small relation suggests that the influence of frequency of home mathematical activities on mathematical ability is minimal. Consequently, this raises questions around whether frequency of home mathematical activities would be a beneficial target for interventions to improve early mathematical skills, as the small relation would indicates that increasing frequency of home mathematical activities would result in minimal gains to early mathematical ability. It is important to note that the meta-analysis found large variation in effect sizes not only between studies but also within studies. It may be that frequency of home mathematical activities plays an important role for early mathematical ability under certain circumstances or in certain populations, but not others. Identifying factors that may increase or decrease the strength of relation would be beneficial for directing future research and interventions in this area. Moderator analyses were conducted to explore whether the hypothesised moderators: study design, geographical location of data collection, age of children, and measure of mathematical activity used, could shed light on why large variation in effect sizes are seen, and thus potentially indicate under which circumstance frequency of home mathematical activities may have the biggest influence on early mathematical ability.

The first moderator explored was whether a study looking at the relation between frequency of home mathematical activities and mathematical ability at a single time point or across multiple time points influenced the strength of relation found between frequency of home mathematical activities and mathematical ability. The moderator analysis found that while the relation was stronger for studies which explore the relation at a single time point than across multiple time points, this was not significant. This finding was similar to Daucourt et al.'s (2021) finding when looking at the wider home mathematical environment. This indicates that study design does not significantly explain the variation seen in effect sizes between frequency of home mathematical activities and mathematical ability.

The second moderator explored was the geographical location of data collection. This was explored as there is substantial variation in the geographical locations where studies have been conducted. It was hypothesised that geographical location may play a role in variation in effect size due to differences in access parents have to early years services and the age children begin school (Bertram et al., 2016; OECD, 2019). Studies were grouped into three geographical locations: North America, Central Europe, and the United Kingdom (UK). However, the geographical location of data collection was not found to moderate the relation between frequency of home mathematical activities and mathematical ability. Thus, indicating that geographical location does not explain the large variation in effect sizes between frequency of home mathematical activities and mathematical ability. However, it is important to note that 19 independent samples fell outside of these geographical regions. It is possible that with more studies across the world, enabling us to look at more specific geographical locations, the role of geographical location for the strength of relation between frequency of home mathematical activities and mathematical ability may change.

The third moderator investigated was the age of children. It was hypothesised that the relation between frequency of home mathematical activities and mathematical ability may change as children become older due to the types of activities taking place at home. Age was not found to be a significant moderator of the relation, which aligns with Daucourt et al.'s (2021) finding when looking at the wider home mathematical environment. This indicates that age does not explain variation in the relation between frequency of home mathematical activities and mathematical ability.

The final moderator explored was the type of mathematical ability measure a study used. Within the literature, studies use a range of mathematical ability measures from composite measures through to measuring individual mathematical skills. It was hypothesised that frequency of home mathematical activities may have a larger influence on some mathematical skills than others. Mathematical ability measures were divided into the following categories: composite, counting, numerical knowledge, magnitude estimation, spatial skills, and non-symbolic. The most common measure was a composite measure (where multiple mathematical skills were tested and combined to give a single overall score, this included both researcher developed composites and standardised tests), whereas the least common measure was spatial skills. Due to the small number of studies using a spatial skill measure of mathematical ability, spatial skills were not able to be investigated as a moderator. Interestingly, type of mathematical ability measure was found to be a significant moderator, with studies using a composite and number knowledge measure of mathematical ability explaining significantly more variance than studies using magnitude estimation measures between frequency of home mathematical activities and mathematical ability. However, there remained significant unexplained heterogeneity in the data after these moderators. There were no other significant differences in mathematical ability measure. This indicates that the way studies measure mathematical ability does influence the relation found between frequency of home mathematical activities and mathematical ability, but that other factors, not measured here, are likely to play a role. It is possible that the types of activities frequently asked about in questionnaires focus least on activities which nurture numerical magnitude development, thus resulting in these differences.

The small overall effect found in the current meta-analysis may indicate that when thinking about the best ways to support early mathematical development, focusing on frequency of home mathematical activities may not be a particularly effective. This would perhaps suggest that future research should move away from exploring frequency of home mathematical activities for mathematical ability. However, there are a number of limitations of this literature which are important to consider before this conclusion can be drawn.

Firstly, all of the studies included in the current review focus on frequency that parents engage in home mathematical activities with their children. However, there is little consensus in the literature about which home mathematical activities parents should be asked about with many studies asking about different mathematical activities (e.g., DeFlorio & Beliakoff, 2015; Lefevre et al., 2009; LeFevre et al., 2010) . A commonly used scale is the scale developed by LeFevre et al. (2009) however, there is no detail about how this scale was constructed. This appears to be a criticism of the literature more widely with studies not detailing how the activities were derived. It may be that some scales used better capture the types of mathematical activities parents are doing with their children than others, thus leading to variation in effect sizes. However, the exception to this comment are two studies: Cahoon et al. (2021) and Study Three reported in Chapter Four of this thesis. Both of these studies used a home mathematical activities measure which was rigorously developed through parent interviews (see Cahoon, et al., 2021; Cahoon et al., 2017), however, neither study found a significant relation between home mathematical activities and mathematical ability.

It is possible that the self-report nature of frequency of home mathematical activities does not accurately capture the frequency of home mathematical activities taking place. This is supported by research comparing questionnaire data with semi-structured interview data on home mathematical activities which found they did not correlate with one another (Mutaf

Yıldız et al., 2018). This is incredibly problematic for relying on the findings of the current literature to draw wider conclusions about the role of home mathematical activities as it may be that self-report questionnaires simply do not adequately capture the frequency that parents are engaging in specific home mathematical activities with their children.

Secondly, home mathematical activities questionnaires comprise of a range of activities which are each likely to be beneficial to different mathematical skills. For example, questionnaires frequently ask about counting objects, as well as weighing out ingredients, or telling the time (e.g., Cahoon, et al., 2021b; DeFlorio & Beliakoff, 2015; Lefevre et al., 2009). We may expect that these questions tap into different mathematical skills, for example, counting objects may support cardinal principal development whereas, weighing out objects may be more likely to support numerical magnitude, we would not necessarily expect telling the time to relate to non-symbolic number knowledge. By aggregating the frequency scores of these activities, either by averaging together (e.g., Dearing et al., 2012; Zippert & Ramani, 2017), or dividing into subscales such as formal vs. information (e.g., DeFlorio & Beliakoff, 2015; Lefevre et al., 2009; this distinction is further discussed in Chapter One), we may be losing the sensitivity to detect how these activities influence mathematical ability. Therefore, if we want to better understand the role of frequency of home mathematical activities, it is important to move towards understanding how mathematical activities which may nurture specific mathematical skills relate to said mathematical skill. This may involve grouping activities based on the mathematical skill they are most likely to support, and measuring that mathematical ability. It is likely that this will be best investigated through interventions which would provide a causal test of whether activities to support certain mathematical skills support those specific mathematical skills.

Thirdly, it is possible that the role of frequency of home mathematical activities varies by demographic factors such as SES, which was not able to be explored in the current meta-analysis due to limitations in the way SES was reported across studies. Unfortunately, many papers did not report SES sample information, or information was not reported in a consistent way. This made it difficult to compare SES across studies, and in particular, across countries. Thus, the decision was made to not to look at SES in this analysis, as we did not feel the data enabled meaningful conclusions to be drawn. It is possible that children from higher-SES families, who are more likely to have resources to support home mathematical learning, would benefit more from home mathematical activities than children from low-SES families with fewer resources (Bradley & Corwyn, 2002). Indeed, this was found in Dunst et al.'s (2017) meta-analysis which explored the influence of the general home mathematical environment on mathematical ability. If this held true for frequency of home mathematical activities, this may go some way in explaining the SES disparities visible in mathematical ability when children begin school (Blakey et al., 2020). An important recommendation for developmental psychology more widely, is to consistently report the SES of the sample to enable conclusions to be drawn about how the SES of a sample may influence the strength of relation found.

Despite the small relation found in the current meta-analysis, the wider limitations of the literature, which have been discussed above, make it difficult to draw meaningful conclusions about the importance of frequency of home mathematical activities for early mathematical ability. If we are to gain a more meaningful understanding of the role of home mathematical activities, it is important that future research moves beyond questionnaires. This may include observational data recorded in the home either through video or voice recordings to better capture the types of mathematical activities taking place, the frequency of these activities, the length of time these activities are engaged in, as well as the quality of engagement in these activities. Furthermore, it is important to emphasise that correlation does not equal causation. Intervention research will be crucial in determining the causal effects of home mathematical activities on mathematical ability. Moreover, causal research may help to shed light on the relation between specific mathematical activities (e.g., counting based activities) on specific mathematical abilities which arise in the early years (e.g., counting ability and cardinal principal knowledge).

In conclusion, the present meta-analysis is the first quantitative synthesis of the relation between frequency of home mathematical activities and mathematical ability in young children. While it is evident that the strength and direction of effect sizes both between- and within- studies vary widely, this meta-analysis found an overall small positive relation between frequency of home mathematical activities and mathematical ability. Type of mathematical ability measure moderated the relation between frequency of home mathematical activities and mathematical ability, with the relation being stronger for composite- and number knowledge- measures in comparison to magnitude estimation measures. No moderation effects were found for other mathematical ability measures, study design, geographical location of data collection, nor child age. This meta-analysis indicates that frequency of home mathematical activities has only a small effect on mathematical ability, which may lead one to conclude that increasing frequency of home mathematical activities will yield minimum benefit to mathematical ability. However, before this conclusion can be reached a number of limitations within the field, including how we measure frequency of mathematical ability, must be addressed.

Chapter Six
An Exploration into Young Children's Home Mathematical Environment during the COVID-19 Pandemic

The COVID-19 pandemic has caused unprecedented disruption to schooling around the world. In the UK, most children have missed over half a year of in-person schooling. During this time, many children's only access to learning has been in the home. However, we know little about what home learning has been taking place in the pandemic. The current study aimed to examine variation in home mathematical learning, and its possible predictors: SES, parent beliefs about mathematics, parent self-efficacy of mathematics, how difficult parents have found supporting their child's mathematical learning, and the barriers parents have faced to supporting their child's learning. The final sample comprised of 434 parents of children aged between three- and seven- years. There was substantial variation in both the hours spent on- and the frequency of- home mathematical activities. Parent beliefs about the importance of mathematics as well as how difficult they reported finding supporting their child's mathematical learning were predictors of this variation. Notably, SES and parent mathematical self-efficacy did not relate to home mathematical learning. Parents reported a range of barriers to home learning which are discussed. These timely findings are important to support children's learning as disruption to education continues, but also to mitigate the impact of this unprecedented disruption to learning moving into the future.

6.1. Introduction

In 2020 the COVID-19 pandemic caused over one billion children and young people across the world to be absent from school, with disruption to schooling continuing into 2022 in many parts of the world (UNESCO, 2020, 2022). In the United Kingdom, schools closed for the majority of children from 23th March 2020, with the exception of children of essential workers or those deemed most vulnerable. Since then, UK children have officially missed approximately 27 weeks of schooling (UNESCO, 2022). Figure 6.1 details the timeline of school closures and reopenings in England since March 2020. However, for many children the amount of time lost is likely to be much larger as a result of (i) contracting COVID-19, (ii) self-isolation due to contact with COVID-19, or (iii) unofficial school closures due to staff shortages as a result of COVID-19 (Roberts & Danechi, 2022). During these school closures, many children's only access to learning has been in the home. Early research in the pandemic has shown large variability in the time parents spent engaging in educational activities with their children (Andrew, et al., 2020). This is concerning as these disparities in learning opportunities may align with existing inequalities in attainment, thus raising questions not only of the impact that school closures may have on children's longer term academic development and attainment, but also about the exacerbation of existing inequalities in educational attainment. Given the closure of education settings globally is unprecedented, there is little previous research that can help us understand the impact of the closure of education settings on children's educational development and future attainment. Research from school strikes in Canada tells us that school closures of just ten days can have large effects on attainment, with mathematical attainment being most affected, in comparison to attainment in reading and writing (Baker, 2013). We currently have little understanding of what may influence differences in the home learning environment during the pandemic. In the present study, we aim to identify the level of variation in mathematical home learning during COVID-19 for young children, and explore factors that may explain this variation. Gaining a better understanding of the key factors influencing home learning may help educators anticipate and support children's outcomes.

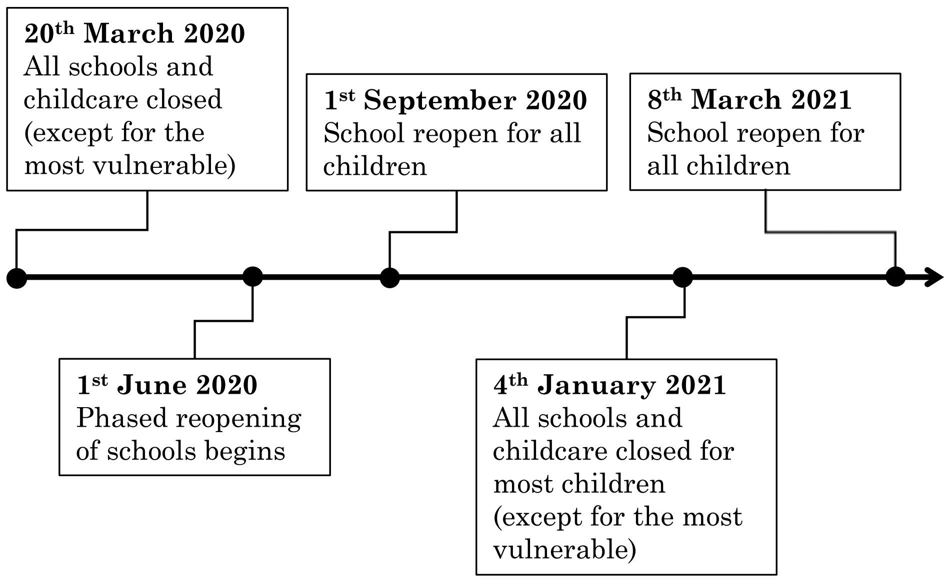


Figure 6.1 Details the dates of when schools closed and reopened due to COVID-19 in England (Roberts & Danechi, 2022).

Given that early mathematical achievement is one of the strongest predictors of later overall attainment (Duncan et al., 2007), it is particularly concerning that mathematical attainment has previously been found to be most disrupted from school closures (Baker, 2013). The hierarchical nature of mathematical learning means that early disparities in mathematical skill, which are visible before children begin school and widen throughout schooling (Klibanoff et al., 2006), often lead to cumulative disadvantage as early skills lay the foundations on which more advanced skills are built (Wynn, 1995). Indeed, there are some early clues as to how the pandemic and school closures have affected children's learning. Early evidence in the UK shows that children returned to school in Autumn 2020 with large variation in their overall ability (Rose et al., 2021). On average, pupils in Key Stage One were two months behind where they were expected to be in mathematics. The gap however, was largest for the poorest children, with children eligible for Free School Meals approximately six months behind their more advantaged peers (Rose et al., 2021).

In the context of COVID-19, it is likely that variation in the amount of mathematical learning done in the home during school closures has influenced the variability in children's ability as they have returned to school (DiPrete & Eirich, 2006). The amount of home mathematical learning may be particularly important in young children as foundational mathematical skills are rapidly developing. Furthermore, it is likely that young children are more heavily reliant on adults to guide their learning than older children. This is because for young children, their meta-cognitive development is still developing, meaning that young children will find it difficult to guide and regulate their own learning, thus relying on more advanced peers, teachers, or family members to support them with this (Veenman et al., 2006). It is therefore important to understand the differences in home mathematical learning during the pandemic, and importantly the factors that drive these differences in parents' ability to engage in these activities. This will enable schools to support children who may be at risk of falling further behind in a classroom context.

Early pandemic research showed large variability in home learning for children aged between four- to fifteen- years between April and June 2020, when schools were closed for the majority of UK children (Andrew, et al., 2020). During this time, most children's only opportunities for learning would have been within the home. What is particularly concerning is that within this study, the authors found that the hours spent on general home learning related to household income, with children living in higher-income families doing significantly more home learning than children in lower-income families. Therefore, it is likely that existing disparities in academic skills will be widened as a result of the differing levels of home activities children have received while schools have been closed. However, this research focused on a large age range, and it is likely that in older children, learning is less parent directed than in younger children. Furthermore, this study focused on a wide range of home learning, thus limiting the conclusions we can draw specifically about home mathematical learning in the pandemic.

Looking to pre-pandemic literature, the home mathematical environment has been shown to positively relate to children's mathematical ability (Daucourt et al., 2021). More specifically, Chapter Five of this thesis highlighted that for younger children, frequency of home mathematical activities relates to early mathematical ability. While the meta-analyses indicated that this relation is small, during the pandemic where children's *only* access to learning has been in the home, we may expect this relation to strengthen. The pandemic therefore provided the ideal window on which to examine variation in home mathematical activities, as well as to understand predictors of this variation.

It is advantageous to identify factors that may relate to variation in home mathematical learning in order to be able to best support children's learning through continued disruption to education due to COVID-19. By drawing on existing literature exploring factors that may explain variation in home mathematical learning prior to the pandemic (e.g., Elliott & Bachman, 2018a, 2018b), as well as pandemic literature on home learning more broadly (e.g., Andrew, et al., 2020), we identified five factors that may be important in explaining variation in home mathematical learning during the pandemic. These factors were SES, parent beliefs, parent self-efficacy, how difficult parents have found supporting their child's mathematical learning, and the barriers parents have faced in supporting their child's mathematical learning.

The first factor, SES, has previously been found to relate to mathematical activities, with higher-SES parents doing a higher frequency of mathematical activities than lower-SES parents (Melhuish et al., 2008; Napoli et al., 2021). However, this relation is equivocal, as other studies, such as those displayed in Chapter Three and Chapter Four of this thesis, have not found a relation. Though, research during the pandemic has indicated that disparities in home learning do align with income, with children from higher-income households doing more learning activities than children from lower-income households (Andrew, et al., 2020). It is likely that the stressors of the pandemic have disproportionately affected lower-SES households, as they are least likely to be able to work from home, and most likely to be under increased financial strain (Blundell et al., 2020). Thus, it is highly conceivable that these factors may influence parents' ability to do home learning with their child and therefore, we may expect any SES disparities in home learning to be exaggerated during the pandemic. This is because children will be even more reliant on the learning resources parents have within their home, and we know that children in higher-SES households have access to more learning resources than children from lower-SES households (Bradley & Corwyn, 2002; Christensen et al., 2014; Crosnoe et al., 2010; Hackman et al., 2015). During the pandemic so far, there are SES disparities in the availability of both learning resources and study space (Andrew, et al., 2020). This indicates that SES may be influencing the amount of home learning during the pandemic, however, the influence of SES of mathematical activities specifically remains unknown.

The second factor is parent beliefs about the importance of mathematics. Some pre-pandemic research has indicated that parent beliefs about the importance of mathematics is related to the frequency that they engage in home mathematical activities (DeFlorio & Beliakoff, 2015; Sonnenschein et al., 2012). Although, this relation was not found in Chapter Two of this thesis. It is reasonable to expect that a relation between parent beliefs about the importance of mathematics and mathematical activities would be compounded during the pandemic. This is because during this time, parents have often been solely responsible for their child's learning. Thus, we may expect that parents who believe mathematical learning to be more important will dedicate more time and resource to mathematical learning than parents who consider mathematical learning to be less important.

The third factor is parents' own self-efficacy of mathematics, which describes how confident parents feel in their own mathematical ability. It is conceivable that parents who feel more confident in their own mathematical ability will feel more empowered to engage in mathematical learning with their children than parents who have lower mathematical self-efficacy. Indeed, previous research has indicated that children of parents who feel anxious about mathematics have a lower mathematical ability than children of parents who do not feel anxious about mathematics (Maloney et al., 2015). While Chapter Two of this thesis did not find parent self-efficacy of mathematics to relate to frequency of mathematical activities, like parent beliefs about mathematics, we may expect this relation to be compounded during the pandemic when parents are solely responsible for their child's mathematical learning.

The fourth factor is how difficult parents have found supporting their child's mathematical learning. It is highly plausible that parents who report finding it more difficult to support their child's mathematical learning will engage in less mathematical learning than parents who find it easier to support their child's mathematical learning. Andrew et al. (2020) found large variation in how difficult parents have found supporting their primary school age child's mathematical learning during COVID-19, with some parents reporting not finding supporting learning at all difficult, while other parents report finding it very difficult to support learning. However, we do not know how these difficulties supporting learning may relate to the amount of mathematical learning taking place in the home.

Related to difficulties in supporting mathematical learning, the fifth factor is the barriers parents face to supporting mathematical learning. It is possible that the types of barriers parents face to supporting their child's mathematical learning influences the home mathematical learning which has taken place during COVID-19. Indeed, the UK government highlights that resources, time, and parent knowledge to be barriers to home learning outside of the pandemic (National Literacy Trust, 2018). It is likely that these barriers are compounded due to the pressures of the pandemic. Furthermore, it is possible that these barriers will have socioeconomic gradients, for example, lower-SES parents who are less likely to be able to work from home may be more likely to report time as a barrier than higher-SES parents (Blundell et al., 2020).

The current study focused on the variation in home mathematical activities parents have done with their child during COVID-19. Prior work has indicated that home mathematical activities support mathematics learning (Daucourt et al., 2021). The study focused on younger children as, for many, the home is the only place learning opportunities will have arisen. Furthermore, younger children are likely to be most reliant on parent guided learning. The study focused on children between three- and seven- years, as this is when early mathematical skills are developing. However, it is important to note that children begin formal schooling in this period (around age four). Therefore, it is plausible that home mathematical activities vary depending on whether children have begun formal schooling or not.

The aim of the current study was to examine variation in the time spent on home mathematical activities, and the frequency of home mathematical activities during COVID-19. The study explored factors which may predict this variation. Five factors were explored to see if they explained variation in home mathematical learning: (i) SES (as measured by parent education and IMD), (ii) parent beliefs about the importance of mathematics, (iii) parent mathematical self-efficacy, (iv) how difficult parents have found supporting mathematical learning during the pandemic, and (v) the barriers parents have faced to mathematical learning.

6.2. Method

6.2.1. Participants

Four hundred and fifty parents completed the online survey. Parents were recruited by advertising the survey on social media platforms between July and August 2020. Twelve participants were excluded due to missing essential data (e.g., child age). Four surveys were excluded due to the child being home schooled prior to the pandemic, as the pandemic would likely not have significantly changed these children's access to education. A total of 434 surveys were included in the final sample (423 mothers, 9 fathers, 1 stepmother and 1 adoptive parent) of children aged between three and seven years (200 females, 213 males and 21 unknown sex, M_{age} = 59 months, range = 36-95 months). Twenty-seven parents reported being essential workers, however, while eligible, these children did not continue to attend school throughout the pandemic. A power calculation showed that 143 survey responses would be sufficient for identifying a relation based on six variables predicting frequency of home mathematical activities (with power set at .80, alpha .05 and based on a small effect size).

The ethnicity breakdown for the children was 89.3% White British, 3.5% White-other background, 0.4% Black, 1.6% Asian, 4.8% Mixed ethnicity, 0.4% missing. SES was calculated using two measures: IMD and parent highest level of education. IMD was derived from household postcode; for parent education, the questionnaire asked for their highest level of education from a set list, ranging from 'no formal qualifications' to 'postgraduate degree or similar'. The European Qualification Framework (European Commission, 2018) was used to score the qualification, which ranged from 0 (lowest level of education) to 7 (highest level of education). All respondents reported their highest level of education, 44 respondents did not provide a postcode meaning we were unable to calculate IMD for 10% of the final sample. The socioeconomic distribution of the sample, displayed in Figure 6.2, showed diverse Index of Multiple Deprivation however, the education level of the sample was skewed to more highly educated parents. 78% of parents in our sample had completed higher education. This was above the national average where 50% of UK adults have a higher education qualification (Department for Education, 2019).

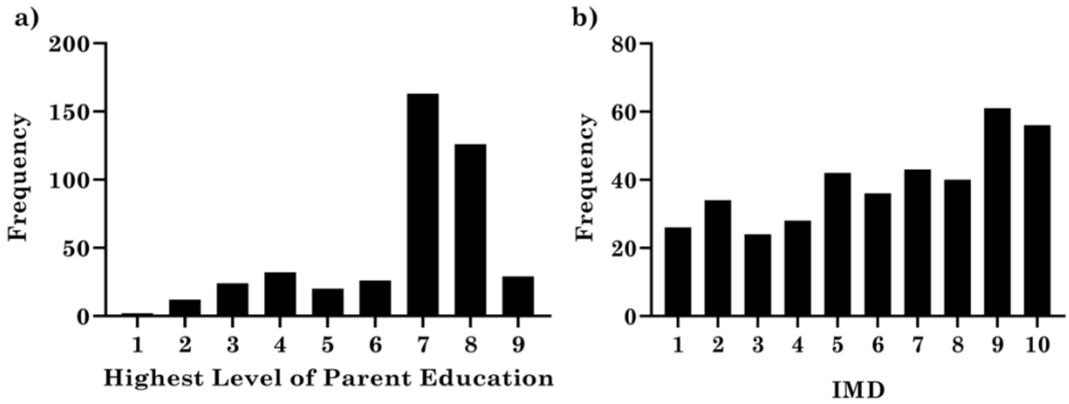


Figure 6.2 The SES distribution of the sample as indexed by a) highest level of parent education (where 0 is the lowest and 7 is the highest level of education), and b) the neighbourhood deprivation measure IMD (where 1 represents the most deprived neighbourhoods and 10 represents the least deprived neighbourhoods).

6.2.2. Questionnaire

Parents completed an online survey using the survey platform Qualtrics. The survey included questions on family demographics, SES, home mathematical activities, parent beliefs about the importance of mathematics, parent mathematical self-efficacy, how difficult parents have found supporting their child's mathematical learning, and the barriers to home mathematical learning parents have experienced (see Appendix 1d for questionnaire items).

Home Mathematical Learning: The study contained two measures of mathematical learning. The first measure was parent reported frequency of home mathematical activities adapted from (Cahoon, et al., 2021a). Parents rated how frequently they engaged in 26 home mathematical activities with their child in the past month – for example, counting objects, playing timed games, or teaching children about money. Frequency was measured using a five-point Likert scale with the answers ranging from 'activity did not occur' to 'almost daily' (coded zero to four respectively). Total scores were calculated by adding up the scores for each question (ranging from 0 to 104). Secondly, parents reported the total number of hours spent on mathematical activities during a typical week since the pandemic began using a sliding scale (ranging 0 to 50 hours) (Andrew, et al., 2020). Parents were also asked how time spent on home mathematical learning has changed from before the pandemic to during the pandemic on a Likert rating scale with the answers ranging from 'much less time' to 'much more time' (coded one to five respectively).

Parent beliefs about the importance of mathematics was measured with a questionnaire adapted from the questionnaire used in Chapter Two, with questions from Sonnenschein et al. (2012), as well as questions developed by Dr Jo Van Herwegen and her research team. Parents rated how strongly they agreed or disagreed with seven statements relating to their beliefs about the importance of mathematics – for example, mathematics is a worthwhile and necessary subject, a strong mathematical background helps in adult life, and it is important for children to develop their mathematical skills. Beliefs about the importance of mathematics was measured using a five-point Likert scale with the answers ranging from 'strongly disagree' to 'strongly agree' (coded one to five respectively). Total scores were calculated by adding up the scores for each question (ranging from 0 to 35).

Parent mathematical self-efficacy was measured with a questionnaire adapted from (Sonnenschein et al., 2012). Parents rated how strongly they agreed or disagreed with seven statements relating to their own mathematical self-efficacy – for example, when I was in school, I enjoyed mathematics, I am confident in my mathematical abilities, I find mathematical activities enjoyable. Mathematical self-efficacy was measured using a five-point Likert scale with the answers ranging from 'strongly disagree' to 'strongly agree' (coded one to five respectively). Total scores were calculated by adding up the scores for each question (ranging from 0 to 35).

Difficulties and barriers to engaging in activities: Parents were asked to record how difficult they have found supporting their children's mathematical learning during COVID-19 and before COVID-19 on a Likert rating scale (1 to 4) from 'not at all difficult' to 'very difficult'. Parents were also asked to select which of the following barriers they had faced to mathematical learning: having time, having knowledge of the topic, having the resources, child's attention. Parents were asked to list any 'other' barriers they had faced that were not listed in a free text box. Fifty-four parents gave free text responses in the 'other' category which were coded by the research team. Twenty-four of the responses were coded into the existing categories. Twenty-two responses reported having multiple children to be a barrier, therefore, a new category 'multiple children' was created. We reasoned that this should be its own category as while it may have constrained parent time or ability to have resources due to this, it could also reflect multiple constraints or something entirely different (having to manage distractions that may arise when siblings are working in the same area). Eight responses did not fit into a category, and thus were not analysed further.

6.3. Results

6.3.1. Descriptive Statistics

Analyses were conducted using SPSS. A binary category for age was created based on whether children were in their preschool years <4 years, or primary school years >4 years. Data were first examined to check the assumptions for the planned parametric statistical tests. All variables were visually inspected using histograms which revealed the variables parent education, change in time spent on mathematical activities pre-covid and during-covid, beliefs about mathematics and self-efficacy of mathematics were negatively skewed. The variables hours spent doing mathematical activities, difficulty supporting mathematical learning pre-covid were positively skewed. All other variables were normally distributed. Therefore, both Spearman and Pearson correlations are reported in the correlation table. The correlations in bold indicate whether Pearson or Spearman correlation coefficients should be interpreted, which also corresponds to which correlation is reported in the text. T-tests were conducted with bias corrected accelerated bootstrapping based on 1000 samples. Correlations and descriptive statistics are displayed in Table 6.1. It is important to note that multiple comparisons were conducted which were not included in the power calculation. We believe it is important to include comparisons given the exploratory nature of this study due to the novelty of the COVID-19 pandemic. Therefore, these comparisons can provide important insight into the educational landscape in the home during COVID-19.

Table 6.1 Spearman's (bottom left) and Pearson's (top right) Correlation Coefficients Measures (Raw Scores).

	N	*M(SD)*	1	2	3	4	5	6	7	8	9
1. IMD	390	6.24(2.86)		.31***	-.02	**.03**	.09	-.04	**.02**	.08	.07
2. Parent Education	434	6.66(1.76)	**.30*** **		-.02	.09	.13**	-.23***	-.15**	.16**	.30***
3. Hours spent on Mathematical activities	426	5.48(4.69)	**-.01**	**-.03**		.35***	.18***	-.09	-.14**	.12*	-.01
4. Frequency of mathematical activities	434	81.44(17.52)	.03	**.09**	**.38*** **		.12*	-.19***	**-.23*** **	.24***	.08
5. Change in time spent on mathematical activities (pre-Covid to during-Covid)	434	3.74(1.08)	**.08**	**.08**	**.33*** **	**.07**		-.17**	-.14**	.25***	.19***
6. Difficulty supporting mathematics learning pre-Covid	434	3.09(1.65)	**-.03**	**-.22*** **	**-.17*** **	**-.20*** **	**-.15** **		.57***	-.16**	-.23***
7. Difficulty supporting mathematics learning during-Covid	434	3.74(1.62)	.01	**-.16** **	**-.22*** **	-.25***	**-.13** **	**.53*** **		-.06	-.22***
8. Parent Beliefs	431	35.36(3.43)	**.09**	**.14** **	**.13** **	**.24*** **	**.19*** **	**-.17*** **	**-.07**		.45***
9. Parent Self-Efficacy	434	24.95(6.79)	**.07**	**.29*** **	**.03**	**.08**	**.14** **	**-.22*** **	**-.22*** **	**.44*** **	

Note. Spearman correlations are displayed in the bottom left corner and Pearson correlations are displayed in the top right corner. *N* = number of participants for each measure. The correlations in bold meet the assumptions and should be interpreted. *M* = mean, *SD* = standard deviation. $p < .05$. $^{**}p < .01$. $^{***}p < .001$.

Ten percent of respondents reported that a member of their household had been shielding (i.e., asked not to leave their homes and minimise face-to-face contact). At the time of the survey, 5.1% respondents said that their child had continued to attend childcare (i.e., nursery/ school/ child minder) throughout lockdown, 48% reported that their child had returned to childcare since it had begun to reopen, 22% reported that they were eligible to return to childcare but had not yet returned, 16% reported that their child was not yet eligible to return, and 8% responded with 'other'.

Prior to COVID-19, only 21% of parents reported that they were most responsible for their child's mathematical learning, with 72% of parents saying that nursery or school was most responsible. However, the majority of parents reported an increase in time spent doing home mathematical activities since COVID-19 (62%), compared to 10% who reported spending less time doing home mathematical activities since COVID-19.

6.3.2. Was there variation in time spent doing home mathematical activities?

There was substantial variation in both the hours parents reported doing home mathematical activities in an average week during the pandemic (M = 5.48, SD = 4.69) and the frequency of home mathematical activities during the past month (M = 81.44, SD = 17.52). The distribution of time spent on home mathematical activities and the frequency of home mathematical activities is displayed in Figure 6.3.

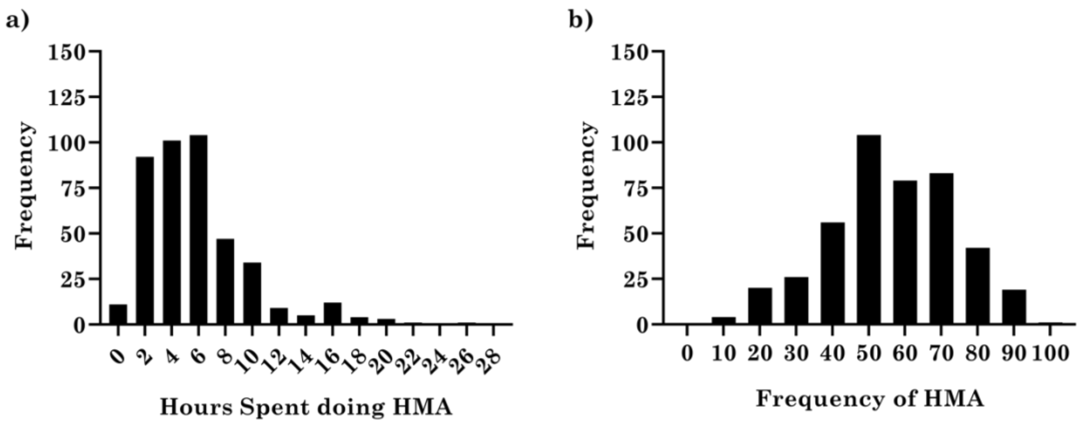


Figure 6.3 Displays the frequency distribution of a) hours spent doing home mathematical activities during an average week in the pandemic, and b) frequency of home mathematical activities during the past month.

6.3.3. Did home mathematical activities differ by whether children had begun formal education or not?

There was no significant difference in hours spent on home mathematical learning for children who had not started formal education (N = 233, M = 5.46, SD = 5.51), compared to those who had (N = 192, M = 5.51, SD = 3.47), $t(397) = -.10$, $p = .940$. However, parents with a child who had not yet begun formal education reported engaging in a higher frequency of home mathematical activities with their child (N = 55, M = 76.35, SD = 19.47), compared to parents with a child who had begun formal education (N = 370, M = 82.14, SD = 17.18), $t(423) = 3.13$, $p = .006$.

6.3.4. Did the variation in home mathematical activities relate to socioeconomic status?

Hours spent doing home mathematical activities did not significantly correlate with parent highest level of education ($r_s(424) = -.03$, $p = .543$), or IMD ($r_s(384) = -.01$, $p = .818$). Similarly, frequency of home mathematical activities did not significantly correlate with parent highest level of education ($r_s(432) = .09$, $p = .072$), or IMD ($r_s(388) = .03$, $p = .530$). This indicates that neither the time spent doing home mathematical activities nor the frequency of home mathematical activities was related to SES.

6.3.5. Did the variation in home mathematical activities relate to parent beliefs about the importance of mathematics?

Parent beliefs about the importance of mathematics significantly positively correlated with hours spent doing home mathematical activities ($r_s(421) = .13$, $p = .009$), and frequency of mathematical activities ($r_s(429) = .24$, $p < .001$), with parents who believed mathematics to be more important spending significantly more hours per week on home mathematical activities and reported a higher frequency of mathematical activities with their child than parents who believed mathematics to be less important.

6.3.6. Did the variation in home mathematical activities relate to parent self-efficacy of mathematics?

Hours spent doing home mathematical activities did not significantly correlate with parent mathematical self-efficacy ($r_s(424) = .03$, $p = .603$), nor did frequency of home mathematical activities ($r_s(432) = .08$, $p = .098$).

6.3.7. Did the variation in home mathematical activities relate to the how difficult parents have found supporting their child's mathematical learning during COVID-19?

How difficult parents found supporting their child's mathematical learning pre-COVID-19 and during COVID-19 is displayed in Figure 6.4. A paired samples t-test revealed that, on average, parents found it more difficult to support their child's mathematical learning during COVID-19 (M = 3.74, SD = 1.62) compared to before COVID-19 (M = 3.09, SD = 1.65), $t(433) = -.84$, $p < .001$.

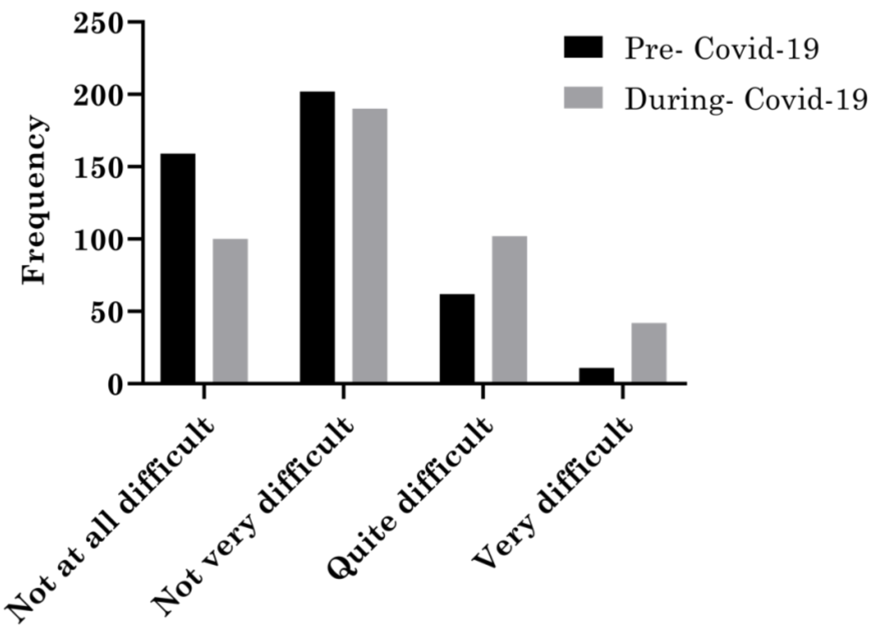


Figure 6.4 How difficult parents rated supporting their children's mathematical learning pre-covid verses during-covid.

Hours spent doing home mathematical activities significantly correlated with how difficult parents found supporting their children's mathematical learning during COVID-19 ($r_s(424) = -.22$, $p < .001$), with parents who have found supporting mathematical learning more difficult spending significantly fewer hours doing mathematical learning than parents who have found support their child's mathematical learning less difficult. Frequency of home mathematical activities also significantly correlated with how difficult parents' found supporting their child's mathematical learning ($r_s(432) = -.25$, $p < .001$), with parents who found supporting mathematical learning more difficult doing a significantly lower frequency of home mathematical activities than parents who have found support their child's mathematical learning less difficult.

6.3.8. Did the barriers parents face to home mathematical learning effect home mathematical activities?

The frequency that parents reported facing the barriers: time, resources, knowledge, attention, and multiple children are reported in Figure 6.5.

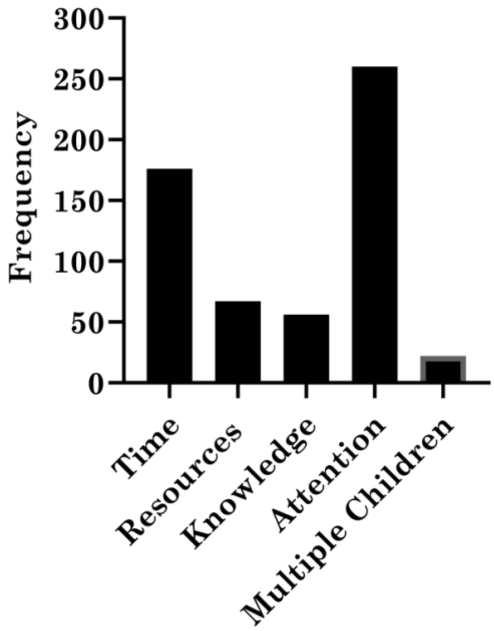


Figure 6.5 Frequency parents reported barriers to supporting their children's mathematical learning during COVID-19 (a total of 581 barriers were reported across 372 parents).

Independent samples *t*-tests were conducted to explore whether the barriers parents reported experiencing to home mathematical learning differed by SES. The *t*-tests reported in Table 6.2 indicate that higher-SES parents were significantly more likely to report time as a barrier to mathematical learning than lower-SES parents. Whereas, lower-SES parents were significant more likely to report their child's attention as a barrier to mathematical learning than higher-SES parents. No other differences were significant.

Table 6.2 Results of *t*-test's showing how the barriers parents reported facing differed by SES for parent education and IMD.

	Barrier	*M*	*SD*	MD	*t(df)*	*p*	95% CI	*M*	*SD*	MD	*t(df)*	*p*	95% CI
		Parent Education						IMD					
Time	Yes	6.87	1.59	-0.38	-2.12(364)	.031	-0.72, - 0.46	6.61	2.85	-0.63	-2.15(387)	.034	-1.23, -0.12
	No	6.50	1.87					5.98	2.85				
Resource	Yes	6.51	1.78	0.16	0.64(80)	.529	-0.34, 0.70	6.07	2.79	0.19	.48(387)	.611	-0.55, 1.01
	No	6.67	1.77					6.26	2.88				
Knowledge	Yes	6.60	1.76	0.05	0.19(387)	.836	-0.42, 0.62	6.28	2.73	0.05	-0.13(387)	.895	-0.85, 0.76
	No	6.65	1.78					6.22	2.88				
Attention	Yes	6.45	1.83	0.48	2.71(354)	.010	0.14, 0.82	5.99	2.75	0.61	2.08(387)	.036	0.05, 1.15
	No	6.94	1.64					6.60	2.99				
Multiple Children	Yes	6.95	1.28	-0.33	-0.82(387)	.272	-0.89, 0.28	7.19	2.58	-1.01	-1.58(387)	.071	-2.08, 0.11
	No	6.63	1.80					6.18	2.87				

Note. Barrier = yes if parent reported experiencing the barrier, and no if parent did not report experiencing the barrier. *M* = Mean, *SD* = Standard Deviation, MD = Mean Difference, *df* = degrees of freedom, *CI* = Confidence Intervals reported with bias corrected accelerated (BCa) bootstrapping based on 1000 samples.

How barriers impacted the time spent on- and frequency of- home mathematical activities for each of these barriers is reported below.

Time. Parents who reported time to be a barrier to home mathematical learning spent significantly fewer hours on home mathematical learning (N = 174, M = 4.90 , SD = 4.27), compared to parents who did not report time to be a barrier (N = 251, M = 5.89, SD = 4.94), $t(423) = 2.15$, $p = .024$. Furthermore, parents who reported time to be a barrier engaged in a significantly lower frequency of home mathematical activities (N = 174, M = 78.85, SD = 17.78), compared to parents who did not report time to be a barrier (N = 251, M = 83.15, SD = 17.25), $t(423) = 2.49$, $p = .017$.

Resources. There was no significant difference in hours spent on home mathematical learning for parents who experienced resources to be a barrier (N = 67,M = 5.37, SD = 5.13), compared to those who did not (N = 358, M = 5.50, SD = 4.62), $t(423) = 0.20$, $p = .130$. There was no significant difference in frequency of mathematical activities for parents who experienced resources to be a barrier (N = 67, M = 78.24, SD = 19.68), compared to those who did not (N = 358, M = 81.98, SD = 17.12), $t(423) = 1.45$, $p = .132$.

Knowledge. There was no significant difference in hours spent on home mathematical learning for parents who experienced knowledge to be a barrier (N = 55, M = 5.27, SD = 4,13), compared to those who did not (N = 370, M = 5.51, SD = 4.78), $t(423) = .35$, $p = .683$. However, parents who reported knowledge to be a barrier engaged in a significantly lower frequency of home mathematical activities (N = 55, M = 76.35, SD = 19.47), compared to parents who did not report knowledge to be a barrier (N = 370, M = 82.14, SD = 17.18), $t(423) = 0.35$, $p = .033$.

Attention. Parents who reported attention to be a barrier to home mathematical learning spent significantly fewer hours on home mathematical learning (N = 258, M = 5.08, SD = 4.52), compared to parents who did not report attention to be a barrier (N = 167, M = 6.11, SD = 4.91), $t(423) = 2.22$, $p = .042$. Furthermore, parents who reported attention to be a barrier engaged in a significantly lower frequency of home mathematical activities (N = 258, M = 78.52, SD = 17.92), compared to parents who did not report time to be a barrier (N = 167, M = 85.82, SD = 16.11), $t(423) = 4.27$, $p < .001$.

Multiple Children. There was no significant difference in hours spent on home mathematical learning for parents who experienced having multiple children to be a barrier (N = 22, M = 5.50, SD = 2.76), compared to those who did not (N = 403 M = 5.48, SD = 4.78), $t(423) = -0.02$, $p = .971$. There was no significant difference in frequency of mathematical activities for parents who experienced having multiple children to be a barrier (N = 22, M = 86.00, SD = 18.70), compared to those who did not (N = 403, M = 81.14, SD = 17.50), $t(423) = -1.27$, $p = .213$.

6.3.9. What predicted hours spent doing home mathematical activities?

To examine which variables predicted hours spent doing mathematical activities, a three-model hierarchical multiple regression was conducted that included variables that significantly correlated or differed with hours spent doing mathematical activities, controlling also for SES (IMD and parent education), and level of schooling.

Assumptions for the regression analyses were checked. The assumptions of linearity, multicollinearity and homoscedasticity were met, but the assumption of normality of residuals was violated. In order to meet the assumption of normality of residuals, a log10+1 transformation was applied to the dependent variable hours spent doing home mathematical learning.

The results are displayed in Table 6.3. In Model 1, SES (IMD and parent education), and level of schooling were entered. In Model 2, parent beliefs about mathematics were entered. In Model 3, difficulty supporting mathematical learning and the presence of two barriers Time and Attention were entered (coded as dummy variables).

Table 6.3 Results of the hierarchical regression analysis predicting hours spent doing home mathematical activities.

	Predictor	***b* (95% confidence intervals)**	***SE B***	***B***	***p***
Model 1	Constant	0.71 (0.60, 0.83)	0.06		<.001
	SES (IMD)	0.00 (-0.01, 0.01)	0.01	.03	.636
	SES (Parent education)	-0.00 (-0.01, 0.10)	0.01	-.02	.653
	Level of Schooling	0.05 (0.06, 0.63)	0.03	.09	.089
Model 2	Constant	0.34 (-0.01, 0.01)	0.15		.020
	SES (IMD)	0.00 (-0.02, 0.01)	0.01	.02	.707
	SES (Parent education)	-0.01 (-0.02, 0.10)	0.01	-.05	.392
	Level of Schooling	0.04 (0.00, 0.02)	0.03	.07	.157
	Parent beliefs about mathematics	0.01 (0.00, 0.02)	0.00	.14	.006
Model 3	Constant	0.51 (0.21, 0.81)	0.15		.001
	SES (IMD)	0.00 (-0.01, 0.01)	0.01	.03	.564
	SES (Parent education)	-0.01 (-0.03, 0.01)	0.01	-.07	.221
	Level of Schooling	0.05 (-0.00, 0.11)	0.03	.10	.053
	Parent beliefs about mathematics	0.01 (0.00, 0.02)	0.00	.13	.011
	Difficulty supporting mathematics learning	-0.02 (-0.04, 0.00)	0.01	-.14	.018
	Barrier: Time	-0.03 (-0.09, 0.02)	0.03	-.06	.251
	Barrier: Attention	-0.04 (-0.10, 0.02)	0.03	-.07	.196

Note. Hours spent of mathematical learning were transformed using log10. R^2 = .01 for Model 1, Δ R^2 = .02 for Model 2, Δ R^2 = .04 for Model 3. Pairwise deletion was used for missing data. SE = Standard Error.

In Model 1, SES (IMD and parent education) and level of schooling were not significant predictors, but accounted for 1% of variance in hours spent doing home mathematical learning ($F(3,382) = 1.09$, $p = .353$). In Model 2, parent beliefs about the importance of mathematics accounted for 3% of variance in hours spent doing home mathematical learning ($F(1,381) = 7.55$, $p = .006$). In Model 3, difficulty supporting mathematics learning was a significant predictor of hours spent doing home mathematical learning, but the barriers time and attention were not significant predictors. The final model accounted for 7% of variance ($F(3,378) = 5.21$, $p = .002$).

6.3.10. What predicts frequency of home mathematical activities?

To examine which variables predicted frequency of home mathematical activities, a three-model hierarchical multiple regression was conducted that included variables that significantly correlated with hours spent doing mathematical activities, controlling for SES (IMD and parent education), and level of schooling.

Assumptions for regression analysis were checked. The assumptions of linearity, multicollinearity and homoscedasticity, and normality of residuals was met.

The results are displayed in Table 6.4. In Model 1, SES (IMD and parent education), and level of schooling were entered. In Model 2, parent beliefs about mathematics were entered. In Model 3, difficulty supporting mathematical learning and the barriers Time, Knowledge, and Attention were entered.

Table 6.4 Results of the hierarchical regression analysis predicting frequency of home mathematical activities.

	Predictor	b (95% confidence intervals)	*SE* B	*β*	*p*
Model 1	Constant	78.37 (71.0, 85.71)	3.74		<.001
	SES (IMD)	-0.02 (-0.65, 0.62)	0.32	-.00	.961
	SES (Parent education)	0.83 (-0.21, 1.86)	0.53	.08	.117
	Level of Schooling	-5.24 (-8.73, -1.74)	1.78	-.145	.003
Model 2	Constant	37.39 (19.55, 55.23)	9.07		<.001
	SES (IMD)	-0.07 (-0.69, 0.55)	0.31	-.00	.817
	SES (Parent education)	0.45 (-0.57, 1.46)	0.52	.08	.387
	Level of Schooling	-6.15 (-9.56, -2.74)	1.74	-.145	<.001
	Parent beliefs about mathematics	1.25 (0.75, 1.75)	0.25	-.00	<.001
Model 3	Constant	50.03 (31.74, 68.31)	9.30		<.001
	SES (IMD)	-0.04 (-0.65, 0.57)	0.31	-.01	.903
	SES (Parent education)	0.25 (-0.76, 1.27)	0.52	.03	.623
	Level of Schooling	-5.06 (-8.42, -1.70)	1.71	-.14	.003
	Parent beliefs about mathematics	1.16 (0.67, 1.65)	0.25	.23	<.001
	Difficulty supporting mathematics learning	-1.21 (-2.39, -0.02)	0.61	-.11	.047
	Barrier: Time	-2.78 (-6.37, 0.82)	1.83	-.08	.130
	Barrier: Knowledge	-2.20 (-7.20, 2.81)	2.55	-.04	.389
	Barrier: Attention	-4.84 (-8.45, -1.22)	1.84	-.14	.009

Note. R^2 = .31 for Model 1, ΔR^2 = .06 for Model 2, ΔR^2 = .06 for Model 3. Pairwise deletion was used for missing data. SE = Standard Error.

In Model 1, level of schooling was a significant predictor (with preschool children doing a higher frequency of activities than children who had begun formal education), accounting for 3% of variance, SES (IMD and parent education) was not a significant predictor ($F_{(3,383)}$ = 4.05, p = .008). In Model 2, introducing parent beliefs about the importance of mathematics accounted for 9% of variance in frequency of home mathematical activities ($F_{(1,382)}$ = 24.28, p < .002). In Model 3, difficulty supporting mathematics learning and the barrier child's attention were a significant predictor of frequency of home mathematical activities, but the barriers knowledge and time were not significant predictors. The final model accounted for 15% of variance ($F_{(4,378)}$ = 6.35, p < .001).

6.4. Discussion

The aim of the current study was to explore variation in the hours spent on- and frequency of- home mathematical activities during the COVID-19 pandemic. The study explored five factors that may explain this variation: SES, parent beliefs about the importance of mathematics, parents' mathematical self-efficacy, how difficult parents found supporting mathematical learning during the pandemic, and the specific barriers parents have faced.

The current study found that there was substantial variation in both the hours spent doing home mathematical activities and the frequency of home mathematical activities during the pandemic. Parents whose child who had not yet begun formal education reported a significantly higher frequency of home mathematical activities than parents whose child had begun formal education. Hours spent on home mathematical activities did not significantly differ by whether a child had started formal education or not. Parents' beliefs about mathematics, and how difficult parents reported finding supporting their child's mathematical learning, predicted both the hours spent doing mathematical learning as well as the frequency of mathematical activities. Parents reported a range of barriers to supporting mathematical learning, with their child's attention being the most frequently reported barrier, followed by time, resources, knowledge, and having multiple children. Higher-SES parents were more likely to report time to be a barrier than lower-SES parents. Lower-SES parents were more likely to report their child's attention to be a barrier. There were no other significant SES differences in barriers. Parents who reported time and attention as barriers did significantly fewer hours of mathematical activities, and a lower frequency of mathematical activities than parents who did not report these barriers. Parents who reported knowledge to be a barrier engaged in a significantly lower frequency of home mathematical activities than parents who did not. No other barriers caused significant differences in the hours spent on- or frequency of- home mathematical activities. However, only the barrier child's attention predicted frequency of mathematical activities. The study did not find that

SES (neither parent education or IMD) nor parent self-efficacy of mathematics related to variation in home mathematical activities.

The study highlights that there is substantial variation in both the hours parents have spent with their child on home mathematical activities and frequency of home mathematical activities during the pandemic. This is concerning as it would indicate that as children are returning to school, the amount of exposure they each will have had to mathematical learning during school closures will be different, thus likely resulting in disparities in mathematical ability. Thus, it is important for schools to understand what may have caused this variation in order to work to support those children who are most at risk of falling behind. However, what is promising is that more broadly, parents reported being more responsible for their child's mathematical learning during COVID-19 than prior to COVID-19.

It was surprising that parents of children who have not yet begun formal education reported a higher frequency of mathematical activities than parents of children who had begun formal education. However, the hours parents reported spending on home mathematical activities with their child did not differ whether children had begun formal education or not. It is possible that differences were seen for frequency- and not hours- of home mathematical activities due to the frequency measure asking about a predetermined list of mathematical activities. It is possible that the survey asked about activities which were more developmentally appropriate to children who were yet to begin formal education as the survey was developed with parents of preschool children (Cahoon, Cassidy, et al., 2021a). Thus, it may be that the activities did not adequately capture the activities parents were doing with their child who has begun formal education. This would explain why parents of children once they had begun school reported doing less of these types of activities. None the less, it is beneficial to know that there is large variation in the home mathematical learning taking place in the home during the pandemic.

It is interesting that the disparities in home mathematical learning do not relate to SES in the current sample. This differs from Andrew et al. (2020) who found that parent income related to the hours of home learning activities taking place in the home. It is possible that the influence of SES of home mathematical learning differs to other forms of learning, thus explaining this difference in the finding. However, this is not a compelling explanation as there is no clear reason why the relation would be different specifically for mathematical learning. Equally SES did not relate to frequency of activities, which is in line with the findings in Chapter Two and Chapter Four of this thesis. Taken together, this could suggest that there is no relation between home mathematical activities and SES in younger children, and this may instead emerge as children get older. While we might expect parental input to be greater for younger children who need more scaffolding in their learning, perhaps as mathematics gets more complex and requires more resources, gradients in family input by

SES become apparent. Given that Andrew et al. (2020) looked at a larger age range, with children between four- and fifteen- years, this may go some way in explaining the disparate findings. However, it is important to highlight that the current sample was considerably skewed, with the majority of parents being university educated. It is possible that if the sample had been more diverse, these findings would not hold, and that SES differences would be visible between the lowest- and highest- SES families.

Parent beliefs about the importance of mathematics were found to be an important predictor of time spent on home mathematical learning and frequency of mathematical activities. Parents who believed mathematics to be more important engaged in more hours - and a higher frequency- of home mathematical activities. This supports our finding in Chapter Two, as well as previous research which has found parent beliefs about the importance of mathematics to relate to the mathematical activities they are doing (Sonnenschein et al., 2012). This finding is important moving into the future as it demonstrates the importance of equipping parents with the knowledge of the importance of mathematics. National Literacy campaigns to encourage parents to understand the benefits of reading have been successful in increasing reading in the home (Save the Children, 2016). Thus, lessons could be learnt to help parents understand the importance of mathematics and encourage more mathematical learning in the home.

Parent self-efficacy of mathematics was not found to relate to either hours spent doing mathematical learning or frequency of home mathematical activities. This is in line with the findings in Chapter Two of this thesis, as well as Sonnenschein et al.'s (2012) findings. It is possible that in younger children where mathematical activities involve foundational mathematics which are not considered complex, parents' confidence in their own mathematical ability plays less of a role in the activities they do. Given that the pandemic is likely to exacerbate the relation between parental factors and mathematical activities, this gives further evidence that in younger children, parent self-efficacy of mathematics does not drive differences in mathematical learning in the home.

Predictably, the difficulty that parents reported in supporting their children's mathematical learning did relate to both hours of mathematical learning and frequency of home mathematical activities. What is interesting is that parents reported finding it significantly more difficult to support their child's mathematical learning during COVID-19 than prior to the pandemic. It is likely that this is related to the fact that parents report an increased feeling of responsibility for their child's mathematical learning, as before the pandemic parents could rely on other sources to support their child's learning such as playgroups, preschools, and schools.

To further investigate the difficulties parents faced, we explored specific barriers to mathematical learning. Parents' most frequently reported barrier to mathematical learning was their child's attention, followed by time, resources, knowledge, and having multiple children. Parents who reported the barriers time and attention engaged in significantly fewer hours- and a lower frequency- of home mathematical activities compared to parents who did not report these as barriers. Furthermore, parents who reported their own knowledge to be a barrier engaged in a lower frequency of mathematical activities compared to parents who did not report this barrier, but knowledge did not relate to time spent on home mathematical activities. No other barriers resulted in significantly differences to time spent on- or frequency of- home mathematical activities. However, when predicting variance in home mathematical activities, only the barrier child's attention predicted frequency of mathematical activities. This is interesting as lower-SES parents were more likely to report their child's attention as a barrier. Though these barriers may not have had a large direct influence on mathematical learning taking place in the home, this is crucial information to be able to support parents into the future.

While the current study has identified large variation in both the hours spent on- and frequency of- mathematical activities in the pandemic, the factors explored to explain this variation only explained a very small proportion (7% for hours spent on home mathematical activities and 15% for frequency of home mathematical activities). It is likely that variables not explored in the current study have influenced this variation. For example, whether parents were furloughed (i.e., workers who were temporarily released from work but still paid) may have influenced the variation. It is conceivable that parents who were furloughed had more time to spend one home learning compared to parents who were juggling working from home with home learning, or parents who could not work from home. Another factor which may be important is the level of support within the family, for example whether a family had access to a child-care bubble (where children could move across households for child-care), or whether a household had multiple people to share the home learning across.

An important limitation to raise of the current study is that it was unable to take a measure of children's mathematical ability. This was due to the limitations of the pandemic meaning that data collection could only take place online. This means that, while this study sheds light on variation in home mathematical learning during the pandemic, we cannot be certain that these disparities in home learning have resulted in differences in children's ability as they return to school.

Despite the study limitations, the findings of this study make a timely contribution to understanding children's mathematical learning in the home during the unprecedented COVID-19 pandemic. The results show great variation in children's home learning experiences, which may explain any disparities in learning outcomes that may arise in the near future. The results support the empirical chapters in this thesis that SES and parent self-efficacy around mathematics does not correlate with parent reported home mathematical activities. Furthermore, the beliefs parents hold about mathematics and the difficulties they face in home mathematical learning appear to be important predictors of the extent to which they engage in mathematical learning activities at home during the pandemic.

Chapter Seven
General Discussion

In this final discussion chapter, I will summarise the background to the research conducted, highlight the research gaps this research aimed to address, and restate the aims of this thesis. I will summarise the studies presented in this thesis and their key findings. I will then discuss how the key findings help us to better understand how early socioeconomic attainment gaps in mathematical skills arise. I will conclude by discussing the implications and limitations of the research and provide direction for future research.

7.1. Thesis Aims and Summary of Key Findings

The aim of the thesis was to identify mechanisms by which socioeconomic attainment gaps in early mathematical ability arise. The research presented in this thesis focused on mechanisms both at a child-level and home-level. Four factors were explored across five studies: verbal ability, inhibitory control, working memory, and frequency of home mathematical activities (as well as how parent cognitions about mathematics relate to SES and frequency of mathematical activities). These factors were chosen because they represent both child- and home-level factors that (i) relate to early mathematical ability and (ii) show socioeconomic gradients. Overall, the research presented in this thesis demonstrates that there are socioeconomic disparities in mathematical ability in children as young as three years of age. Differences in inhibitory control and verbal ability may, in part, explain how these socioeconomic differences arise. Working memory does not appear to explain SES disparities, but did emerge an important factor for early mathematical development. Frequency of home mathematical activities did not explain SES attainment gaps in mathematics. In the empirical research, frequency of home mathematical activities did not relate to mathematical ability, but when reviewing the field as a whole, a small relation was found. SES did not relate to frequency of home mathematical activities across the empirical studies or during the COVID-19 pandemic – a time when we hypothesised if a relation was to exist it may be found at a time when families – especially low SES families – may be under pressure. However, a number of future research directions are recommended before frequency of home mathematical activities can be ruled out as a mechanism by which SES attainment gaps in early mathematics arise.

7.2. Background and Research Gaps

Previous research has shown pervasive socioeconomic disparities in children's mathematical ability, with these inequalities visible on entry to formal education, and not only remaining but widening across schooling (Caro et al., 2009; DeFlorio & Beliakoff, 2015). Early mathematical ability is a predictor of how long a person will remain in education, their educational attainment, their future income, and their health (Duncan et al., 2007a; Ritchie & Bates, 2013b; Wagstaff et al., 2001). Thus, disparities in early mathematical ability contribute to perpetuating cycles of socioeconomic inequality (Office for National Statistics, 2014). Therefore, decreasing SES gaps in early mathematical ability may be important for reducing these disparities and their associated negative effects throughout society. However, until now, there has been limited exploration into the factors by which attainment gaps in mathematical ability arise prior to the start of formal education.

The studies presented in this thesis aimed to address three important gaps in the literature. Firstly, while it is clear multiple factors influence the development of socioeconomic attainment gaps, many previous studies have focused only on a single factor rather than multiple factors, thus limiting our understanding of how these SES gaps arise. Secondly, many studies have not recruited diverse socioeconomic samples making it difficult to draw conclusions about how the influence of factors may vary across the SES spectrum. Thirdly, much of the research has been conducted in children once they have begun school, but we know disparities emerge prior to the start of school. This is a problem because if we are to understand and prevent SES disparities, it is important to know what factors influence the emergence of these disparities. Consequently, this thesis aimed to explore multiple factors that may influence the SES attainment gap in mathematics in children from diverse SES background before they began formal education.

7.3. Summary of Studies and their Main Findings

Study One, Chapter Two utilised secondary data to explore the role of frequency of home mathematical activities in explaining SES disparities in mathematical ability in preschool aged children. The study also explored the role of parent cognitions (i.e., their beliefs about the importance of mathematics and their own mathematical self-efficacy) in explaining the hypothesised relation between SES and frequency of home mathematical activities. The home environment was an important factor to explore given that SES disparities appear before children begin school. Parents completed a questionnaire that asked about the frequency they engage in a range of predetermined mathematical activities in the home, their beliefs about the importance of mathematics, their own mathematical self-efficacy, as well as information about their SES. Children's mathematical skills were assessed using a standardised mathematical measure (TEMA). The study found socioeconomic disparities in early mathematical ability. Frequency of home mathematical activities was not found to explain these SES disparities, as frequency of home mathematical activities did not relate to early mathematical ability, nor did they vary by SES. Parents who believed mathematics to be more important engaged in a higher frequency of home mathematical activities than parents who believed mathematics to be less important. However, parent beliefs did not vary by SES. Parent self-efficacy neither related to frequency of home mathematical activities or SES. This suggests that frequency of home mathematical activities are not a mechanism by which SES influences early mathematical ability. However, there were several limitations of this study which limited our ability to draw a firm conclusion on this. While the study did contain children from diverse SES backgrounds, the sample was skewed to higher-SES families. Additionally, the frequency of home mathematical activities measure used in this study was developed with a Canadian sample and therefore may not adequately capture the mathematical activities UK parents do with their child. Thus, we aimed to explore this finding further throughout this thesis and also include other potential mechanisms so we could develop a more comprehensive understanding of why SES attainment gaps arise.

Study Two, Chapter Three presented a pilot study which aimed to test measures of cognition to ensure they suitably captured variation in preschoolers' skills from lower-SES backgrounds, before being implemented in two larger studies presented in Chapter Four. Many cognition measures which have previously been used in research have been used with higher-SES children. Given that children from lower-SES backgrounds, on average, have a lower ability than children from higher-SES backgrounds on measures of executive function and mathematics, it was important to test whether these measures sufficiently captured variation in lower-SES children. The pilot study established that the mathematical activity measures Counting and Give-a-Number, and the inhibitory control measure Black/White Stroop, successfully captured variation in low-SES preschoolers' ability. The working memory measures piloted did not capture variation, with low-SES preschoolers' performance being at floor. Therefore, an alternative working memory measure, which focuses primarily on short-term memory, and has previously been used with low-SES preschoolers was used in Chapter Four.

Chapter Four presented Study Three and Study Four which built upon the secondary data analysis presented in Chapter Two to provide an in-depth exploration into multiple factors at a child-level and home-level that may explain SES attainment gaps in early mathematics. These factors were inhibitory control, working memory, verbal ability, and frequency of home mathematical activities. The first study presented in this chapter used a new measure of frequency of home mathematical activities which was rigorously developed in the UK. Study Three found socioeconomic attainment gaps in early mathematical ability, with inhibitory control and verbal ability helping to indirectly explain these disparities. Working memory did not explain SES disparities, but did appear important for early mathematical ability. Like in Chapter Two, frequency of home mathematical activities did not relate to mathematical ability or vary by SES. However, given the relative novelty of these finding, it was important to test their robustness. Furthermore, the SES sample of Study Three was skewed to *lower-SES families*, again limiting our ability to draw conclusions across the SES spectrum. Thus, we aimed to replicate and build upon these findings in a second study with a truly diverse SES sample. Study Four used the same measures of inhibitory control, working memory, and verbal ability as Study Three, but returned to using the more commonly used measure of frequency of home mathematical activities that was used in Chapter Two. The findings of Study Four, with a diverse SES sample, directly replicated the findings of Study Three in this chapter. The replication suggests we can be more confident in our conclusions: that inhibitory control, and verbal ability are indirect effects by which we see SES attainment gaps in early mathematics, but working memory and frequency of home mathematical activities are not.

Study Five, Chapter Five presented a systematic review and meta-analysis on the relation between frequency of home mathematical activities and mathematical ability in young children. The aim of this quantitative synthesis was to shed light on the disparate relations found between frequency of home mathematical activities and mathematical ability. The meta-analysis found an overall small positive relation (r = .13) between frequency of home mathematical activities and mathematical ability across 73 independent samples with 351 effect sizes. The meta-analysis revealed large variation in findings, both between- and within-studies. This variation was explained, in part, by the type of mathematical ability measure used, but not by age, geographical location, or study design. This indicates that overall, there is a small relation between frequency of home mathematical activities and mathematical ability, but that this varies widely. The moderators explored did not fully explain this variation, thus, we still do not have a good understanding of under what circumstances this relation may be stronger or weaker. Thus, a number of future research directions are discussed below to enable a better understanding of the role of frequency of home mathematical activities on early mathematical ability.

The final study, Study Six in Chapter Six, aimed to explore variation in home mathematical learning during the first wave of the COVID-19 pandemic, and the predictors of this variation. The pandemic provided a unique window of opportunity to explore whether there was a relation between SES and home mathematical activities. This is because it was at a time where we may most expect to see a relation if one did exist. Specifically, low SES families conceivably may have experienced greater hardships in time and resources compared to higher-SES families which may have impacted their ability to engage. Thus, this study explored variation in both the time spent on- and frequency of- home mathematical activities among families of young children in the UK during the pandemic. Additionally, Chapter Six explored five factors that may explain this variation: SES, parent beliefs about the importance of mathematics, parent self-efficacy of mathematics, how difficult parents have found supporting their children's mathematical learning, and the barriers parents have faced to supporting their child's mathematical learning. There was large variation in both the time spent on- and frequency of- home mathematical learning during the pandemic. Interestingly, this variation did not coincide with SES. Parent beliefs about the importance of mathematics, as well as how difficult they find supporting their child's mathematical learning, did predict both the time spent on- and frequency of- home mathematical activities. Parent self-efficacy did not relate to home mathematical activities. Parents reported a range of barriers to home mathematical learning, which included having time and resources, as well as their child's own attention. This information offers important insights on how we might best support families moving into the future and in times of future lockdowns or school closures.

Together, these findings provide a vital first step in identifying factors that may explain why socioeconomic attainment gaps in early mathematical ability arise. This discussion will now draw links across the findings of studies presented in this thesis, considering their contributions to our understanding of how socioeconomic attainment gaps in early mathematical ability emerge.

7.4. Contributions to our Understanding of Socioeconomic Disparities in Mathematical Ability

7.4.1. There are socioeconomic attainment gaps in early mathematical ability

The three studies presented in Chapter Two and Chapter Four of this thesis consistently found that socioeconomic disparities in mathematical ability are visible in children as young as three years of age. These socioeconomic gradients were found using both parent education (a direct measure of SES), as well as IMD (a neighbourhood measure of SES). This is pertinent because a large proportion of research documenting socioeconomic disparities in mathematical ability have done so with children from around the age of five, once they have already started formal education (e.g., Educational Endowment Foundation, 2017). However, the results of this thesis highlight that socioeconomic gradients in mathematical ability have already begun to embed before children begin formal education, adding to the small body of literature showing socioeconomic disparities before children begin school (e.g., Blakey et al., 2020). This emphasises two things. Firstly, that there must be a range of child-level and home-level factors that contribute to SES disparities aside from factors such as school quality, and formal mathematical instruction. Secondly, it reinforces the need to identify the mechanisms by which these attainment gaps emerge before the start of school, rather than once children have begun school and these disparities have embedded (Caro et al., 2009). The identification of *early* mechanisms will enable the development of interventions to narrow SES gradients in early mathematical ability.

7.4.2. Verbal Ability may be important for helping to explain socioeconomic gradients in early mathematical ability.

Verbal ability was found to be a factor which helps to explain socioeconomic attainment gaps in mathematical ability before children begin school. While this finding is relatively novel, the importance of verbal ability in helping to explain SES gaps was replicated across two studies. Furthermore, this finding builds upon two previous studies we know of that have demonstrated verbal ability to mediate the relation between SES and mathematical ability with older children, and in younger children from higher-SES backgrounds (Slusser et al., 2019; Von Stumm et al., 2020). Moreover, this relation was found when controlling for processing speed, which was used as a proxy measure for general cognitive ability (see Chapter One for further discussion). This is pertinent as verbal ability is commonly used as a proxy measure for general cognitive ability, and highlights that verbal ability relates to mathematical ability beyond general basic cognitive ability.

Finding verbal ability is important in explaining the relation between SES and mathematical ability is novel and underexplored, but also perhaps unsurprising. This is because a wealth of research has documented SES disparities in vocabulary (Arriaga et al., 1998; Dollaghan et al., 1999; Fernald et al., 2013; McGillion et al., 2017; Morisset et al., 1990). Furthermore, verbal ability is an essential element of symbolic number skills. To expand, the cornerstone of symbolic mathematical ability, learning the cardinal principal, requires mapping numerical meaning to number words (Xenidou-Dervou et al., 2015). It is possible that higher-SES children, who are more likely to have larger vocabularies, are able to make the key transition from non-symbolic to symbolic number understanding sooner than their lower-SES peers due to their verbal ability. As a result, it is plausible that this leads to higher-SES children being able to develop more advanced mathematical skills earlier than their peers from lower-SES backgrounds. This is supported by Negen and Sarnecka (2012) finding that the age at which children develop cardinal principle knowledge is related to their verbal ability. Additionally, it is possible that children with lower verbal ability may not only have to meet the demands of the mathematical task itself, but also of learning, understanding, and using unfamiliar language when completing mathematical tasks (Meyer, 2000). For example, when thinking about questions in TEMA-3 (the standardised mathematical measure used throughout the studies in this thesis), the questions required children to know number words, understand comparative terms (e.g., more vs. less, or bigger vs. smaller), as well as arithmetic operations (e.g., add and subtract). Children who are less familiar with this vocabulary, not only have to contend with the mathematical problem, but also understanding the vocabulary.

In order to determine if verbal ability is indeed a mediator of the relation between SES and mathematical ability, longitudinal research is required. If longitudinal research supports verbal ability as a mechanism, it is a plausible target path for interventions designed to reduce SES inequalities in early mathematics. The identification of verbal ability as a factor is particularly exciting, as there are already a number of vocabulary interventions which have been found to be effective at improving vocabulary (Marulis & Neuman, 2010). However, these interventions have been found to be most effective for higher-SES children, thus demonstrating that alone, they do not sufficiently close the SES attainment gap (Marulis & Neuman, 2010). Nevertheless, it may be possible to use these existing vocabulary interventions to (i) causally test the relation between verbal ability and early mathematical development, and (ii) to improve early mathematical outcomes for those most at risk.

This thesis has primarily used the term 'verbal ability' to refer to receptive vocabulary. However, it is important to raise the point that there are other types of verbal ability, for example expressive vocabulary, semantics, grammar, pragmatics, and comprehension. While this thesis chose to focus on receptive vocabulary, as there is currently a larger evidence base for the relation between receptive vocabulary and mathematics than other aspects of language (e.g., Cahoon et al., 2021; Purpura et al., 2011), it is important for future research to explore how other elements of verbal ability may relate to early mathematical ability. For example, it is possible that a child's comprehension ability also relates to their mathematical ability, as early mathematical problems are often presented in a story format (e.g., Peter has five sweets, Sarah gives Peter one more, how many sweets does Peter now have?). Thus, it is conceivable that a child with a higher comprehension level would be able to understand the mathematical problem more easily, and perhaps have a lower cognitive load to solve the mathematical problem, than a child with lower comprehension ability.

In addition to future research exploring other forms of verbal ability beyond receptive vocabulary, there is recent evidence that vocabulary which is specific to mathematics may be important for early mathematical ability. A recent meta-analysis across 40 studies found a positive medium effect between mathematical vocabulary and mathematical ability (Lin et al., 2021). However, the age of children in the studies included in this meta-analysis ranged from 4 to 20 years. Thus, less is known about the role of mathematical vocabulary for mathematical ability in the preschool years. Purpura and Reid (2016) did explore mathematical vocabulary in preschoolers, and found a relation between mathematical vocabulary and mathematical ability. Furthermore, they found SES gradients in mathematical vocabulary. Children of parents with less than a college education had lower mathematical vocabulary than preschoolers of parents with more than a college education. This would suggest that future research should also explore the role of mathematics vocabulary in explaining SES disparities in mathematical ability prior to the start of formal education. Together, this future work would help us develop a more fine-grained understanding of whether the relation between vocabulary and mathematics is broad and general, or whether it reflects a specific relation with helping children comprehend mathematical problems or use and understand mathematical language.

7.4.3. Inhibitory Control may be important for helping to explain socioeconomic gradients in early mathematical ability.

Inhibitory control was found, across two studies, to be a factor which helps to explain SES gradients in early mathematical ability. This finding supports existing literature documenting SES gradients in inhibitory control (Blakey et al., 2020; Lawson et al., 2018). As well as supporting research which has shown inhibitory control to be important for early mathematical ability (Allan et al., 2014). This finding brings together these two areas of research, extending our understanding of the role of inhibitory control in explaining SES disparities in early mathematical ability.

It is likely that inhibitory control helps to support early mathematical skills by enabling children to ignore distracting information while focusing on a mathematical problem, as well as helping them to suppress prepotent but incorrect strategies when solving a problem. For example, for children to successfully complete a mathematical problem presented in a story format, they need to suppress less relevant story information and extract the relevant mathematical content. An example of this would be ‘Jane is playing with her sister. Jane has two strawberries, and her sister gives her two more strawberries, how many strawberries does Jane now have?’. In order to solve this, a child will need to suppress the irrelevant information about Jane and her sister, and extract the relevant mathematical content (i.e., 2+1 =3). If the next question was ‘Jane gave her sister back two strawberries, how many strawberries does Jane now have’, the child would now need to suppress their prepotent response to add, as the last question required adding, to apply subtraction to successfully solve the mathematical problem.

It is important to note that there are two types of inhibitory control: interference control (i.e., the ability to selectively attend to particular features of a stimulus while ignoring less relevant features) and response inhibition (i.e., the ability to suppress a previously relevant, but now no longer relevant response) (Gilmore et al., 2015). Gilmore et al. (2015) suggest that both types of inhibitory control are likely to be important for mathematical ability. The Black/White Stroop task, used in the studies in this thesis to measure inhibitory control, relies on both response inhibition and interference control (Montgomery & Koeltzow, 2010b). However, Gilmore et al. (2015) also highlights that that it is possible different types of inhibitory control influence mathematical ability in different ways. For example, it may be that response inhibition is important when switching between operations (e.g., between addition to subtraction problems), whereas interference control may be more important when mathematical problems are presented within a story context. Therefore, it may be beneficial for future research to use tasks that measure only a single type of inhibitory control tasks (e.g., Go/No-Go task which measures response inhibition) to determine how different types of inhibitory control differentially relate to early mathematical skills,

A further distinction that is made within the inhibitory control literature is whether a task is domain general or domain specific. In the context of mathematics, a domain specific task would be one involving mathematical stimuli (e.g., inhibiting numbers). The current study used a domain general task, finding a relation between inhibitory control and mathematical ability. But Gilmore et al. (2015) suggest that the relation between inhibitory control and domain specific tasks may be even stronger. Thus, it may be beneficial for future research to deploy both domain specific and domain general inhibitory control tasks. This may help to isolate which elements of inhibitory control are most strongly related to mathematics, thus enabling more specific interventions to be developed.

Current evidence and theory are somewhat lacking in identifying why SES influences the development of inhibitory control in the early years. There are two existing influential theories that discuss why SES may influence executive functions more generally: the stress model (Blair, 2010) and the cognitive stimulation theory (Rosen et al., 2020). The stress model proposes that SES disparities in executive functions arise due to low-SES children, or more specifically, children in poverty, being more likely to experience early life stressors (both directly and via parenting). Experiencing these stressors results in high exposure to stress hormones, which are thought to impact the development of areas of the brain that underpin executive functions (i.e., the prefrontal cortex) (Blair, 2010). However, this theory only explains why we see SES disparities in the most disadvantaged children, and not across the SES spectrum. This is because we would not expect stress exposure to decrease linearly across the SES spectrum (i.e., there is likely to be a much larger difference in the stress experienced by a child living in poverty, in comparison to a middle-SES child than we would expect between a middle-SES and high-SES child). Alternatively, the cognitive stimulation theory stipulates that SES disparities in executive functions are caused by differences in cognitive stimulation in the home. Higher-SES children are thought to be more likely to live in cognitively stimulating environments, thus supporting the development of executive functions through exposure to language and learning activities (Rosen et al., 2020). While this theory may be better able to explain the SES gradients seen across the full spectrum, 'cognitive stimulation' is a broad category encompassing many factors. These factors include enriching materials, learning resources, parent-child interactions, and linguistic input. These factors are often measured with broad non-specific scales that involve observing the home (for example, items that ask how many books are in the home). Given that cognitive stimulation is such a broad term, at present, the lack of specificity in the theory in linking these factors to executive function development makes it challenging to design targeted interventions.

Promising recent longitudinal research may help us shed light on why we see SES gradients in inhibitory control, and how this links to mathematical skills. Waters et al. (2021) found that inhibitory control mediates the relation between SES and later mathematical ability, but that this relation did not hold when controlling for verbal ability. Importantly, this finding suggests that the pathways from SES to inhibitory control may go via verbal ability. Therefore, SES influences on verbal ability may explain SES differences not only in mathematical skills, but also in inhibitory control. Indeed, Daneri et al. (2019) found that vocabulary mediated the relation between SES and executive functions in children aged three years. Therefore, SES disparities in mathematical skills may begin by SES influencing early verbal ability; this, in turn, may have a knock-on-effect on inhibitory control; which then goes on to influence mathematical ability. This speculation may inform a finer-grained model of how SES attainment gaps emerge. Exploring whether the pathway to SES disparities in mathematical skills goes from SES via vocabulary and inhibitory control longitudinally is an important and interesting future research direction.

The findings of this research suggest that inhibitory control is an important potential mechanism to further explore with longitudinal research. If longitudinal research confirms inhibitory control as a mechanism by which SES disparities in early mathematical ability emerge, interventions for supporting inhibitory control in the early years could be one way of helping to reduce socioeconomic attainment gaps. While Blakey et al. (2020) found cognitive interventions designed to target inhibitory control directly in young children was not effective, they proposed two alternative approaches to early inhibitory control interventions. Firstly, embedding inhibitory control activities within mathematical activities may be one way to support inhibitory control and decrease SES gaps. For example, encouraging children to adopt meta-cognitive strategies to think about both the correct and incorrect answers. This has been found to be an effective approach to improving executive function ability more broadly in children once they've begun school (Blair & Raver, 2014). Secondly, it may be possible for an intervention to support inhibitory control by reducing the incidental cognitive demands on learning tasks, helping to scaffold learning where children have lower executive function ability. An example of this may be reducing the amount of less relevant, distracting information when presenting mathematical problems, so that the child can focus on attending to the mathematical problem. Thus, if longitudinal research does confirm inhibitory control to be a mechanism, these suggested intervention approaches may be beneficial for supporting inhibitory control and reducing SES attainment gaps.

7.4.4. Working Memory is important for early mathematical ability but may not explain socioeconomic gradients.

Working memory was identified to be important for early mathematical ability across both studies in Chapter Four, however, neither study found SES gradients in working memory. This would indicate that working memory is not a factor that helps to explain SES gradients in early mathematical ability. Finding that working memory is important for early mathematical ability does support existing research in which has found working memory to be important for mathematical ability (Agostino et al., 2010; Brookman-Byrne et al., 2018; Cragg & Gilmore, 2014; Gilmore et al., 2015; Lubin et al., 2013; Raghubar & Barnes, 2017; Saracho & Spodek, 2008; Waters et al., 2021).

Despite this thesis indicating that working memory is not a factor that drives SES disparities in mathematics, working memory should not be dismissed as a possible mechanism by which SES gradients in mathematical ability emerge. It is possible that SES gradients in working memory were not found due to the way working memory was operationalised in this thesis. In the studies in Chapter Four, the working memory measure mostly reflected young children's visuospatial recall skills; this contrasts with the more complex working memory measures typically used with older children, which require information to be manipulated and updated. Indeed, previous research has found SES differences in older children where the working memory task had a manipulation element (Blakey et al., 2020; Lawson et al., 2018). Some research suggests that SES gradients are the strongest on cognitive tasks that involve high executive function demands (Farah et al., 2006). In Chapter Two we piloted a more complex working memory task with a manipulation. However, in a low-SES sample this task was too complex and children were at floor on the task, thus it was not capturing variation in working memory ability. As yet, there are no sensitive working memory tasks we are aware of for three-year-olds that require both storage and processing. It would be beneficial for future research to develop such measures that can be used for socioeconomically diverse groups of young children.

A further plausible explanation for why SES gradients were not seen in working memory is that the task was mainly visuo-spatial. Recent work identified working memory as a mediator of attainment gaps when a verbal measure was used (Waters et al., 2021). Therefore, it is possible that socioeconomic gradients would be observed on a verbal measure of working memory. Both verbal and visual working memory have been found to be important for mathematical ability in children of school age (Fanari et al., 2019; Waters et al., 2021). However, we avoided using a verbal memory measure as we did not want this to be really measuring verbal ability. Before any conclusions can be drawn about working memory as a mechanism by which SES gradients emerge before children begin school, it is vital that future research explores SES gradients in both simple and complex visual and verbal working memory tasks.

7.4.5. What role is there for home mathematical activities in explaining socioeconomic gradients?

As socioeconomic gradients in mathematical ability are visible before children begin formal schooling, differences in children's home environment are a likely candidate to influence the SES disparities in early mathematical skills. We hypothesised that frequency of home mathematical activities was one element of the home environment which may influence these disparities. While the empirical studies presented in Chapter Two and Chapter Four of this thesis did show substantial variation in the frequency that parents engage in home mathematical activities, they did not find a relation between frequency of home mathematical and mathematical ability, nor did they find a socioeconomic gradient in frequency of home mathematical activities. Furthermore, Chapter Six which explored predictors of home mathematical activities during COVID-19 – a time where we may expect any SES differences to be exacerbated – did not find SES to relate to either frequency of home mathematical activities or time spent on home mathematical activities. These findings taken together would indicate that home mathematical activities are not a mechanism by which socioeconomic attainment gaps in early mathematical ability arise. However, before this conclusion can be drawn, it is important to discuss these findings in more depth.

It is somewhat surprising that the empirical studies within this thesis did not find a relation between frequency of home mathematical activities and mathematical ability. The absence of relation goes against a widely held belief that practice makes perfect, in other words the more a skill is practised, the better you will become at that skill. However, the findings within the existing literature have yielded contrasting findings, both between studies (i.e., studies with different samples), and within studies (i.e., studies with the same sample but multiple relations). Some studies have shown positive relations, others have reported no significant relation (like the studies in this thesis), or some have even reported a significant negative relation. The meta-analysis reported in Chapter Five helped to shed light on these disparate results, finding that there is an overall small positive effect between frequency of home mathematical activities and mathematical ability, but that there is large variation in effect sizes. This would suggest that frequency of home mathematical activities does relate to early mathematical ability, but that this relation is small. Given the small overall relation found in the meta-analysis, it is possible that the empirical studies presented in this thesis did not find a relation as they powered for a small-medium relation between frequency of home mathematical activities and mathematical ability. Thus, if the studies had a larger sample size, they may have indeed found a significant relation between frequency of home mathematical activities and mathematical ability.

The small overall effect may suggest that when thinking about the best ways to support early mathematical development, focusing on frequency of home mathematical activities may not be a particularly effective factor to focus on. However, it is important to highlight that the meta-analysis indicated large heterogeneity in results which may suggest that there are perhaps certain conditions under which frequency home mathematical activities may be more beneficial for mathematical ability than others. The meta-analysis did find the type of mathematical ability measure used did moderate the relation, with the relation between frequency of home mathematical activities and mathematical ability stronger when a composite mathematical measure or a number knowledge measure was used in comparison to a measure of magnitude estimation. It may be that this is due to the type of mathematical activities asked about in questionnaires. If the activities do not involve magnitude estimation, we may not expect magnitude estimation to relate to the frequency of activities. Whereas a composite measure of mathematical ability measures a range of mathematical skills, making it more likely the activities will tap into some of these skills. This indicates that how effective frequency of home mathematical activities are, depends on the type of mathematical measure used within a study to measure mathematical ability, which is discussed further within Chapter Five. Although, there was still significant unexplained heterogeneity. This would indicate that there are other factors that may influence the strength of relation between frequency of home mathematical activities and mathematical ability.

To make progress in understanding the relation between frequency of home mathematical activities and mathematical ability, and to understand in which circumstances- or populations- intervention may be most effective, it is vital we identify factors that may influence the strength of the relation. One possible moderator, relating to the aims of this thesis, is SES. A previous meta-analysis on the home mathematical environment more generally, did find that the relation between frequency of home mathematical activities was stronger for higher-SES children than lower-SES children (Dunst et al., 2017). Unfortunately, while the meta-analysis in Chapter Five did aim to explore whether SES moderated the relation between frequency of home mathematical activities and mathematical ability, it was not able to do so for three reasons. Firstly, due to some studies not reporting SES information at all (e,g., Huang et al., 2017). Secondly, due to incomplete reporting of SES information (i.e., sample A had higher SES than sample B, without giving any detail on the SES measure used or the SES data, e.g., Lefevre et al., 2009). Finally, the third and largest barrier to assessing SES as a moderator was that the studies were conducted in multiple countries. Cross-country comparisons of SES are notoriously difficult (see Psaki et al., 2014). This is because SES measurements are not standardised across countries but relative within a country. For example, a certain education qualification in North America may put a parent in a lower-SES bracket than the same qualification in Chilli, thus making it difficult to compare the relative SES. This problem is not confined to developmental psychology research, but is a cross-disciplinary issue where one may want to compare SES information across countries (e.g., health research). Thus, this is a wider issue to be solved beyond the realms of developmental psychology research.

There are further reasons to be cautious about dismissing frequency of home mathematical activities as a mechanism by which SES disparities emerge in early mathematics. These reasons relate to the methods used to conduct home mathematical activity research. As discussed in Chapter Five, the majority of research exploring the role of home mathematical activities for early mathematical ability, including the research in this thesis, have done so via parent questionnaires. This method relies on a single caregiver to detail how frequently their child engages in a predetermined set of home mathematical activities. It is likely that a child has exposure to home mathematical activities with other members of the household (e.g., siblings or other caregivers) which may not be adequately captured by a single parent completing a survey. This is supported by research showing siblings play a large role in mathematical activities in the home (Cahoon et al., 2017), as well as research showing differences in the frequency of mathematical activities reported by mothers compared to fathers, with mother's reporting a higher frequency of mathematical activities than fathers, although this was not statistically significant (del Río et al., 2017).

It is also possible that using a predetermined list of mathematical activities in a frequency questionnaire do not reflect the mathematical activities actually taking place in the home. Indeed, Mutaf Yildiz et al. (2018) compared a questionnaire measure- to an observational measure- of home mathematical activities and surprisingly, found they did not correlate. They suggest that different ways of home mathematical activities may capture different types of activities taking place. Therefore, it may be that more direct, observational measures of frequency of home mathematical activities would (i) find socioeconomic gradients, and (ii) more strongly relate to mathematical ability.

A further criticism of the research to date, is that, like the studies in this thesis, they have focused on frequency of mathematical activities. It is important to highlight that frequency is only one element of home mathematical activities. It is possible that the type of mathematical activity parents do, the range of these activities, and the quality of the activities may also be important for early mathematical development. Indeed, language research has shown the importance of quality over quantity for a child's verbal ability (Hirsh-Pasek et al., 2015). However, little work has been done to explore what constitutes quality in the home mathematical environment, and whether quality varies by SES and relates to mathematical outcomes. It is possible SES gradients exist in *range*, *type*, or *quality* of home mathematical activities. For example, when thinking about the general home learning environment, there is a myriad of research showing SES gradients in the learning resources parents have, as well as the quality of interaction (Daucourt et al., 2021; Hackman et al., 2014; Lowe et al., 2013).

Furthermore, when thinking about type of activity, it may be that certain types of activities relate to early mathematical ability more than others (see Andrews et al., 2021). Therefore, a crucial future research direction is to move beyond frequency to measure other elements of the home mathematical environment using alternative methods to parent questionnaire, such as observations. Portable lightweight recording tools, such as LENA, have provided valuable insights into factors that support early language development (eg., McGillion et al., 2017). It may be beneficial for research exploring the home mathematical environment to utilise these methods to understand the types of mathematical interactions taking place in the home (e.g., enabling us to establish whether they are age appropriate), as well as helping us to understand the range and quality (e.g., whether scaffolding is taking place in mathematical interactions) of these interactions. In addition to observational research, intervention research will be crucial to move beyond correlation to identify causal relations.

Chapter Two, Chapter Four, and Chapter Six showed large variation in the amount of home mathematical activities parents do. It is helpful to understand factors that may influence the frequency that parents engage in home mathematical activities, as it may be one factor that is open to intervention to encourage parents to do more activities. Chapter Two and Chapter Six explored whether parent cognitions about mathematics were one of these factors. The Chapters had aimed to explore whether parent cognitions mediated the relation between SES and home mathematical activities, however throughout this thesis, no SES gradients in home mathematical activities were found. Furthermore, the studies which explored parent cognitions were skewed to a higher-SES sample, thus limiting the conclusions that can be drawn about the relation between parent cognitions and SES. Thus, we will focus specifically on explaining the variation observed in mathematical activities.

Both Chapter Two and Chapter Six found that parents who believed mathematics to be more important engaged in a higher frequency of home mathematical activities than parents who believed mathematics to be less important. This suggests that parent beliefs about the importance of mathematics may be an important mechanism to target to increase home mathematical activities. However, neither Chapter Two nor Chapter Six found parent self-efficacy to relate to frequency of mathematical activities. This is possibly due to the age of children, as the mathematical activities they are doing are relatively basic. One might expect parent self-efficacy to play a greater role as children become older and mathematics becomes more complex. Perhaps as mathematics becomes more complex, parental self efficacy around mathematics will shape their ability and confidence to support their children with their mathematical learning. This is discussed more extensively in both Chapter Two and Chapter Four.

The study in Chapter Six, found that parents reported feeling more responsible for their child's learning during COVID-19 than they felt before COVID-19. If parents held more positive beliefs about mathematics, it is highly plausible that they saw engaging in mathematical activities as a priority and thus engaged in more, than parents who held less positive beliefs about mathematics. This finding is consistent with previous research showing parent beliefs do influence the learning parents do in the home with their children (Sonnenschein et al., 2012). Our findings go further to suggest that when parents feel most responsible for their children's learning, their beliefs may play a larger roll. Thus, this has implications for any intervention designed to empower parents to do home mathematical learning with their child.

7.5. Implications of the Findings

The collection of studies presented in this thesis make a timely contribution to understanding how attainment gaps in early mathematical ability emerge. The studies provide a vital first step in identifying multiple plausible mechanisms for future longitudinal research to explore.

The thesis demonstrates that socioeconomic disparities in early mathematical ability are multi-factorial. This supports existing frameworks by which we understand SES disparities, such as the Ecological Systems Model (Bronfenbrenner, 1979), and the Opportunity Propensity Framework (Ribner et al., 2019), both of which were outlined in Chapter One. The thesis demonstrated that the child-level factors verbal ability and inhibitory control are important for explaining SES attainment gaps. We hypothesise that early SES disparities are likely influenced by differences in the home environment given that SES gradients are seen before formal schooling begins. This shows that if we are to gain a comprehensive understanding of how early socioeconomic disparities arise, it is vital that multiple factors at different levels (e.g., home environment factors, as well as child factors) are explored to understand how they relate to one another.

The studies in this thesis provide valuable insights into multiple factors which may help to explain socioeconomic disparities in early mathematical ability. This is poignant as it is possible that the factors identified could be targeted by interventions to help reduce SES gradients in early mathematical ability. For example, it may be possible to use existing interventions to improve verbal ability, which in turn may help to reduce SES gradients in mathematical ability (Marulis & Neuman, 2010). Similarly, it may be possible to display mathematical tasks in a way that reduces executive function demands on mathematical learning, thus helping to narrow attainment gaps. However, the cross-sectional nature of the studies mean that we are unable to confirm whether inhibitory control and verbal ability are, in fact, mechanisms. This is because they only establish a relation at a single time-point and thus, we cannot establish whether they predict growth in a skill. Longitudinal research will be crucial for understanding whether the influence of SES on possible mechanisms compounds over time, and how these factors predict growth in mathematical ability. Only when longitudinal research confirms these factors as mechanisms can interventions be developed and implemented with the goal of decreasing SES disparities and improve outcomes.

The results of the thesis showing frequency of home mathematical activities is not a mechanism to brings into question our understanding of whether home learning activities are a way in which socioeconomic disparities arise. Home mathematical activities were strongly speculated as a mechanism by Elliott & Bachman, (2018). However, as discussed in the home mathematical activities section of this discussion, a number of future research directions are needed before any conclusive conclusions can be drawn about the role of home mathematical activities in explaining disparities in early mathematical ability.

The importance of both inhibitory control and verbal ability align with more specific theories about factors that influence early mathematical development, such as Geary's (2004) framework for identifying how difficulties in mathematics arise which highlight both executive functions and verbal ability, as well as LeFevre et al.'s (2010) pathway to mathematics, which emphasises the importance of verbal ability for mathematics. The current research contributes to these theories by showing that these factors are relevant in children's mathematical development before they have begun formal education, and that they may be important in explaining disparities in mathematical ability.

In Chapter One, the conceptualisation of executive functions was discussed, as some research has suggested in the early years executive functions are better conceptualised as a single factor 'executive function', rather than as individual components (i.e., 'inhibitory control' and 'working memory') (see Wiebe et al., 2011). However, other research has highlighted the benefits of exploring individual components of executive function in individual differences research (see Bull et al., 2008; Lerner & Lonigan, 2014). The research in this thesis took the latter approach, examining individual components (refer to Chapter One for further discussion). The findings of this thesis, that working memory and inhibitory control do not have the same relation to SES and mathematics as one another, fits with past research by Bull et al. (2008) and Lerner & Lonigan (2014), and speaks to the advantages to treating executive functions as separate components when examining individual differences. Thus, it is recommended that future research examining individual differences in executive functions do explore the components separately, given their different relation to SES, and that they are likely to make each make unique contributions to early mathematical development.

7.6. Limitations and Future Research Directions

The largest limitation to the work presented in this thesis is the cross-sectional nature of the studies. The thesis aimed to explore mechanisms by which SES attainment gaps in early mathematical ability emerge. Initially, a longitudinal study was designed for Chapter Four to explore this question. However, due to the restraints on in person research during COVID-19 and nursery closures, the research presented in this thesis was only able to take place at a single time point. Despite this, the research in this thesis makes a significant contribution by providing a clear and robust account of factors that may be of interest in explaining SES gradients. However, before conclusions can be drawn about causal mechanisms, longitudinal research is required to confirm the temporal ordering of the variables. In other words, longitudinal research will enable us to see the order in which mechanisms produce change in mathematical ability over time.

The predictors of attainment gaps, as this work has identified, are likely to be multi-factorial so it will be helpful for future work to examine how multiple predictors like executive functions, verbal ability, *and* the quality of activities in the home predict mathematical attainment gaps as they emerge early on and change over time. Furthermore, longitudinal research will be fundamental in establishing our hypothesised relation that SES disparities in mathematical skills may begin by SES influencing early verbal ability; this, in turn, may have a knock-on-effect on inhibitory control; which then goes on to influence mathematical ability. Through longitudinal research, we will be able to establish whether (i) SES relates to both the development of verbal ability and inhibitory control, (ii) advances in the development of verbal ability predate and relate to advances in the development of inhibitory control, and (iii) whether advances in both verbal ability and inhibitory control relate to mathematical development.

Another limitation of some studies presented in this thesis is that, while this thesis set out to recruit diverse SES samples, not all samples were as diverse as we had aspired to have. The study presented in Chapter Two came from secondary data which consequently meant that we had no control over the SES of the sample recruited. The study was skewed to higher-SES children, meaning that we cannot extrapolate the findings of the study across the SES spectrum. Again, this was a major limitation for the study presented in Chapter Six, which explored home mathematical activities during COVID-19. The nature of the pandemic meant that data had to be collected online. While efforts were made to advertise the study online in locations that would be seen by a diverse sample of the population, such as local community social media groups, the sample was still skewed to higher-SES parents. It is possible that parents who are more highly educated, or experienced in university education, feel most comfortable taking part in university research or research on learning. Samples being skewed to higher-SES is a problem for a significant proportion of developmental psychology research, and it is one that every effort must be made to address if research is to have maximum impact (Bornstein et al., 2013). The first study presented in Chapter Four also suffered from a lack of diverse sample, however, in this study the sample was skewed to *lower-SES*. While it is absolutely more desirable to have a diverse SES sample, a sample skewed to lower-SES children is still incredibly insightful as the majority of research to date, has been conducted in middle/higher-SES samples. The second study presented in Chapter Four did have a truly diverse sample. And thus, it is important for future research to strive to recruit diverse SES samples if we are to gain a comprehensive understanding of how developmental outcomes across the SES spectrum.

As mentioned throughout this discussion, a further limitation of the work is that limited measures were taken for child-level factors. For inhibitory control, working memory, and verbal ability, there are multiple conceptualisations and ways to measure these factors. It is important that future research explores these factors with multiple measures, such as multiple types of verbal ability (including mathematical vocabulary and comprehension), multiple types of inhibitory control (including domain general vs. domain specific and interference control vs. response inhibition), and multiple types of working memory (visuospatial vs. verbal, and tasks with simple recall vs. tasks with a manipulation element). Only when these factors have been fully explored can we begin to build a comprehensive understanding of how these factors may influence SES disparities in early mathematics.

Another limitation of this work is that we relied on two measures of SES throughout this thesis (i) parent education, and (ii) IMD which is a neighbourhood measure. These were chosen as they are most commonly used in research and related to educational outcomes. However, as Duncan & Magnuson (2012) outline, it is likely that multiple SES elements, including income and occupation, relate to developmental outcomes differently. For example, income may influence the types of learning resources available in the home, with higher-income families able to afford a larger range of activities. And therefore, it is possible that income may relate to the types of mathematical resources available in the home, which in turn may influence a child's mathematical development. Thus, it is important for future research to explore the role of other elements of SES and how they relate to SES disparities in early mathematics.

Finally, it is important to raise the limitation that exploring frequency of home mathematical activities relied on parent report in a questionnaire. As mentioned earlier in this discussion, previous research has indicated parent report in a questionnaire does not correlate with observations of home mathematical activities. Therefore, we cannot be sure that the methods used in this thesis do adequately capture the frequency of activities taking place in the home. It is vital that future research moves beyond questionnaires to observational research to truly understand the mathematical activities that take place in the home, as well as intervention research to enable causal links to be drawn. Furthermore, it is important that future research moves beyond looking at *frequency* of home mathematical activities, and explores other elements of home mathematical activities such as *range*, *type*, and *quality* of activity, that may relate to early mathematical ability, as well as have SES gradients.

7.7. Final Conclusions

In conclusion, the research displayed in this thesis has consistently showed socioeconomic attainment gaps in early mathematical ability from as young as age three. This highlights the importance of focusing on mechanisms before children begin formal education. This research provides an important first step to identifying factors that may be mechanisms by which socioeconomic attainment gaps in early mathematical ability arise. Inhibitory control and verbal ability were found to contribute towards explaining socioeconomic attainment gaps, and it is vital longitudinal research explores these further to confirm whether they are mechanisms, and whether disparities in verbal ability *lead to* disparities in inhibitory control. While working memory and frequency of home mathematical activities were not found to be factors that explain SES gradients in mathematical ability, this does not mean they may not be important due to limitations in how they could be measured. These null findings have led to ideas for how future research can make progress building a good robust evidence base to explain early mathematical inequalities.

References

Agostino, A., Johnson, J., & Pascual-Leone, J. (2010). Executive functions underlying multiplicative reasoning: Problem type matters. *Journal of Experimental Child Psychology*, *105*(4), 286–305. https://doi.org/10.1016/J.JECP.2009.09.006

Ahmed, S. F., Tang, S., Waters, N. E., & Davis-Kean, P. (2018). Executive function and academic achievement: Longitudinal relations from early childhood to adolescence. *Journal of Educational Psychology*, *111*(3), 446–458. https://doi.org/10.1037/edu0000296

Allan, N. P., Hume, L. E., Allan, D. M., Farrington, A. L., & Lonigan, C. J. (2014). Relations between inhibitory control and the development of academic skills in preschool and kindergarten: A meta-analysis. *Developmental Psychology*, *50*(10), 2368–2379. https://doi.org/10.1037/a0037493

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: are they separable? *Child Development*, *77*(6), 1698–1716. https://doi.org/10.1111/j.1467-8624.2006.00968.x

Anderson, P. (2002). Assessment and Development of Executive Function (EF) During Childhood. *Child Neuropsychology*, *8*(2), 71–82. https://doi.org/https://doi.org/10.1076/chin.8.2.71.8724

Andrew, A., Cattan, S., Costa-Dias, M., Farquharson, C., Kraftman, L., Krutikova, S., Phimister, A., & Sevilla, A. (2020). *Learning during the lockdown: real-time data on children's experiences during home learning*.

Andrew, A., Cattan, S., Dias, M. C., Farquharson, C., Kraftman, L., Krutikova, S., Phimister, A., & Sevilla, A. (2020). Inequalities in Children's Experiences of Home Learning during the COVID-19 Lockdown in England*. *Fiscal Studies*, *41*(3), 143–5671.

Andrews, P., Petersson, J., & Sayers, J. (2021). A methodological critique of research on parent-initiated mathematics activities and young children's attainment. *Educational Studies in Mathematics*. https://doi.org/10.1007/s10649-021-10080-x

Arriaga, R. I., Fenson, L., Cronan, T., & Pethick, S. J. (1998). Scores on the MacArthur Communicative Development Inventory of children from low and middle-income families. *Applied Psycholinguistics* , *19*(2), 209–223. https://doi.org/10.1017/s0142716400010043

Atkinson, A. L., Hill, L. J. B., Pettinger, K. J., Wright, J., Hart, A. R., Dickerson, J., & Mon-Williams, M. (2022). Can holistic school readiness evaluations predict academic achievement and special educational needs status? Evidence from the Early Years Foundation Stage Profile. *Learning and Instruction*, *77*(August). https://doi.org/10.1016/j.learninstruc.2021.101537

Baker, E. H. (2014). Socioeconomic Status, Definition. In *The Wiley Blackwell Encyclopedia of Health, Illness, Behavior, and Society* (pp. 2210–2214). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118410868.wbehibs395

Baker, Michael. (2013). Industrial actions in schools: Strikes and student achievement. *Canadian Journal of Economics*, *46*(3), 1014–1036. https://doi.org/10.1111/caje.12035

Baroody, A. J., Eiland, M. D., Purpura, D. J., & Reid, E. E. (2012). Fostering At-Risk Kindergarten Children's Number Sense. *Cognition and Instruction*, *30*(4), 435–470. https://doi.org/10.1080/07370008.2012.720152

Bennett, A. (2017). *Early numerical experiences*.

Benton, T., & Sutch, T. (2013). *Exploring the value of GCSE prediction matrices based upon attainment at Key Stage 2* (Issue May).

Bernabini, L., Tobia, V., Guarini, A., & Bonifacci, P. (2020). Predictors of Children's Early Numeracy: Environmental Variables, Intergenerational Pathways, and Children's Cognitive, Linguistic, and Non-symbolic Number Skills. *Frontiers in Psychology*, *11*, 1–15. https://doi.org/10.3389/fpsyg.2020.505065

Bertram, T., Pascal, C., Cummins, A., Delaney, S., Ludlow, C., Lyndon, H., Hencke, J., Kostek, M., Knoll, S., & Stancel-Piatak, A. (2016). *Early Childhood Policies and Systems in Eight Countries Findings from IEA's Early Childhood Education Study*. http://eces.iea.nl

Best, J. R., Miller, P. H., & Naglieri, J. A. (2011). Relations between Executive Function and Academic Achievement from Ages 5 to 17 in a Large, Representative National Sample. *Learning and Individual Differences*, *21*(4), 327–336. https://doi.org/10.1016/j.lindif.2011.01.007

Blair, C. (2010). Stress and the Development of Self-Regulation in Context. *Child Development Perspectives*, *4*(3), 181–188. https://doi.org/10.1111/j.1750-8606.2010.00145.x

Blair, C., & Raver, C. C. (2014). Closing the achievement gap through modification of neurocognitive and neuroendocrine function: Results from a cluster randomized controlled trial of an innovative approach to the education of children in kindergarten. *PLoS ONE*, *9*(11). https://doi.org/10.1371/journal.pone.0112393

Blair, C., & Raver, C. C. (2016). Poverty, Stress, and Brain Development: New Directions for Prevention and Intervention. *Academic Pediatrics*, *16*(3), S30–S36. https://doi.org/10.1016/j.acap.2016.01.010

Blakey, E., & Carroll, D. J. (2015). A Short Executive Function Training Program Improves Preschoolers' Working Memory. *Frontiers in Psychology*, *6*. https://doi.org/10.3389/fpsyg.2015.01827

Blakey, E., Matthews, D., Buck, J., Cameron, D., Higgins, B., Ridley, E., Sullivan, E., & Carroll, D. J. (2020). The Role of Executive Functions in Socioeconomic Attainment Gaps : Results From a Randomized Controlled Trial. *Child Development*, *91*(5), 1594–1614. https://doi.org/10.1111/cdev.13358

Blakey, E., Visser, I., & Carroll, D. J. (2016). Different Executive Functions Support Different Kinds of Cognitive Flexibility : Evidence From 2- , 3- , and 4-Year-Olds. *Child Development*, *87*(2), 513–526. https://doi.org/10.1111/cdev.12468

Blankson, O'Brien, Leerkes, Calkins, & Marcovitch. (2015). Do Hours Spent Viewing Television at Ages 3 and 4 Predict Vocabulary and Executive Functioning at Age 5? *Merrill-Palmer Quarterly*, *61*(2), 264. https://doi.org/10.13110/merrpalmquar1982.61.2.0264

Blevins-Knabe, B., Austin, A. B., Musun, L., Eddy, A., & Jones, R. M. (2000). Family home care providers' and parents' beliefs and practices concerning mathematics with young children. *Early Child Development and Care*, *165*(1), 41–58. https://doi.org/10.1080/0300443001650104

Blevins-Knabe, B., & Musun-Miller, L. (1996). Number Use at Home by Children and Their Parents and Its Relationship to Early Mathematical Performance. *Early Development and Parenting*, *5*(1), 35–45. https://doi.org/https://doi.org/10.1002/(SICI)1099-0917(199603)5:1%3C35::AID-EDP113%3E3.0.CO;2-0

Bliss, S. (2006). Test of Early Mathematics Ability–Third Edition. *Journal of Psychoeducational Assessment*, *24*(1), 85–98. https://doi.org/10.1177/0734282905282839

Blundell, R., Dias, M. C., Joyce, R., & Xu, X. (2020). *COVID-19 and Inequalities**.

Bodovski, K., & Farkas, G. (2008). "Concerted cultivation" and unequal achievement in elementary school. *Social Science Research*, *37*(3), 903–919. https://doi.org/10.1016/j.ssresearch.2008.02.007

Borenstein, M., Hedges, L. v., Higgins, J. P. T., & Rothstein, H. R. (2009). *Introduction to Meta-Analysis*. John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470743386

Bornstein, M. H., Jager, J., & Putnick, D. L. (2013). Sampling in developmental science: Situations, shortcomings, solutions, and standards. In *Developmental Review* (Vol. 33, Issue 4, pp. 357–370). https://doi.org/10.1016/j.dr.2013.08.003

Bradley, R. H., & Corwyn, R. F. (2002). Socioeconomic Status and Child Development. *Annual Review of Psychology*, *53*(1), 371–399. https://doi.org/10.1146/annurev.psych.53.100901.135233

Bramer, W. M., Giustini, D., de Jong, G. B., Holland, L., & Bekhuis, T. (2016). De-duplication of database search results for systematic reviews in endnote. *Journal of the Medical Library Association*, *104*(3), 240–243. https://doi.org/10.3163/1536-5050.104.3.014

Bronfenbrenner, U. (1979). Contexts of child rearing: Problems and prospects. *American Psychologist*, *34*(10), 844–850. https://doi.org/10.1037/0003-066X.34.10.844

Brookman-Byrne, A., Mareschal, D., Tolmie, A. K., & Dumontheil, I. (2018). Inhibitory control and counterintuitive science and maths reasoning in adolescence. *PLOS ONE*, *13*(6). https://doi.org/10.1371/journal.pone.0198973

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology*, *33*(3), 205–228. https://doi.org/10.1080/87565640801982312

Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives*, *8*(1). https://doi.org/10.1111/cdep.12059

Burger, A., & Chong, I. (2011). Receptive Vocabulary. In S. Goldstein & J. A. Naglieri (Eds.), *Encyclopedia of Child Behavior and Development* (p. 1231). Springer US. https://doi.org/10.1007/978-0-387-79061-9_2359

Byrnes, J. P., & Wasik, B. A. (2009). Factors predictive of mathematics achievement in kindergarten, first and third grades: An opportunity-propensity analysis. *Contemporary Educational Psychology*, *34*(2), 167–183. https://doi.org/10.1016/j.cedpsych.2009.01.002

Cahoon, A., Cassidy, T., Purpura, D., & Simms, V. (2021). Developing a Rigorous Measure of the Pre-school Home Mathematics Environment. *Journal of Numerical Cognition*.

Cahoon, A., Cassidy, T., & Simms, V. (2017). Parents' views and experiences of the informal and formal home numeracy environment. *Learning, Culture and Social Interaction*, *15*, 69–79. https://doi.org/10.1016/j.lcsi.2017.08.002

Cahoon, A., Gilmore, C., & Simms, V. (2021). Developmental pathways of early numerical skills during the preschool to school transition. *Learning and Instruction*, *75*. https://doi.org/10.1016/j.learninstruc.2021.101484

Cankaya, Z. O. (2013a). *The Naming of Number Naming Systems and Numeracy Experiences in the Development of Early Numeracy Knowledge: Study 1* [doctoral thesis]. Carleton University.

Cankaya, Z. O. (2013b). *The Naming of Number Naming Systems and Numeracy Experiences in the Development of Early Numeracy Knowledge: Study 3* [doctoral thesis]. Carleton University.

Cannon, J., & Ginsburg, H. P. (2008). "Doing the Math": Maternal Beliefs About Early Mathematics Versus Language Learning. *Early Education & Development*, *19*(2), 238–260. https://doi.org/10.1080/10409280801963913

Caro, D. H., McDonald, J. T., & Willms, J. D. (2009). Socio-economic Status and Academic Achievement Trajectories from Childhood to Adolescence. *Canadian Journal of Education*, *32*(3), 558–590. https://psycnet.apa.org/record/2010-16661-007

Cheng, Y., & Wu, X. (2017). The Relationship between SES and Reading Comprehension in Chinese: A Mediation Model. *Frontiers in Psychology*, *8*(672). https://doi.org/10.3389/fpsyg.2017.00672

Cheung, S. K., Dulay, K. M., & McBride, C. (2020a). Parents' characteristics, the home environment, and children's numeracy skills: How are they related in low- to middle-income families in the Philippines? *Journal of Experimental Child Psychology*, *192*. https://doi.org/10.1016/j.jecp.2019.104780

Cheung, S. K., Dulay, K. M., & McBride, C. (2020b). Parents' characteristics, the home environment, and children's numeracy skills: How are they related in low- to middle-income families in the Philippines? *Journal of Experimental Child Psychology*, *192*. https://doi.org/10.1016/j.jecp.2019.104780

Cheung, S. K., Yang, X., Dulay, K. M., & McBride, C. (2018). Family and individual variables associated with young filipino children's numeracy interest and competence. *British Journal of Developmental Psychology*, *36*(2), 334–353. https://doi.org/10.1111/bjdp.12222

Christensen, D. L., Schieve, L. A., Devine, O., & Drews-Botsch, C. (2014). Socioeconomic status, child enrichment factors, and cognitive performance among preschool-age children: Results from the Follow-Up of Growth and Development Experiences study. *Research in Developmental Disabilities*, *35*(7), 1789–1801. https://doi.org/10.1016/j.ridd.2014.02.003

Ciping, D., Silinskas, G., Wei, W., & Georgiou, G. K. (2015). Cross-lagged relationships between home learning environment and academic achievement in Chinese. *Early Childhood Research Quarterly*, *33*, 12–20. https://doi.org/10.1016/J.ECRESQ.2015.05.001

Collins, M. A. (2016). *The roles of symbolic mapping and relational thinking in early reading and mathematics* [doctoral thesis]. Boston College.

Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in Neuroscience and Education*, *3*(2), 63–68. https://doi.org/10.1016/j.tine.2013.12.001

Crawford, C., & Cribb, J. (2013). *Reading and Maths Skills at Age 10 and Earnings in Later Life: A Brief Analysis Using the British Cohort Study*.

Crawford, C., & Greaves, E. (2013). *A comparison of commonly used socio-economic indicators: their relationship to educational disadvantage and relevance to Teach First*. https://www.ifs.org.uk/comms/r79.pdf

Crosnoe, R., Leventhal, T., Wirth, R. J., Pierce, K. M., & Pianta, R. C. (2010). Family Socioeconomic Status and Consistent Environmental Stimulation in Early Childhood. *Child Development*, *81*(3), 972–987. https://doi.org/10.1111/j.1467-8624.2010.01446.x

Daneri, M. P., Blair, C., Kuhn, L. J., Vernon-Feagans, L., Greenberg, M., Cox, M., Burchinal, P., Willoughby, M., Garrett-Peters, P., & Mills-Koonce, R. (2019). Maternal Language and Child Vocabulary Mediate Relations Between Socioeconomic Status and Executive Function During Early Childhood. *Child Development*, *90*(6), 2001–2018. https://doi.org/10.1111/cdev.13065

Daucourt, M. C., Napoli, A., Quinn, J., Wood, S. G., & Hart, S. A. (2021a). The Home Math Environment and Children's Math Achievement: A Meta-Analysis. *Psychological Bulletin*.

Daucourt, M. C., Napoli, A. R., Quinn, J. M., Wood, S. G., & Hart, S. A. (2021b). The home math environment and math achievement: A meta-analysis. *Psychological Bulletin*, *147*(6), 565–596. https://doi.org/10.1037/bul0000330

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*(11), 2037–2078. https://doi.org/10.1016/j.neuropsychologia.2006.02.006

de Bondt, M., Willenberg, I. A., & Bus, A. G. (2020). Do Book Giveaway Programs Promote the Home Literacy Environment and Children's Literacy-Related Behavior and Skills? *Review of Educational Research*, *90*(3), 349–375. https://doi.org/10.3102/0034654320922140

de Keyser, L., Bakker, M., Rathé, S., Wijns, N., Torbeyns, J., Verschaffel, L., & de Smedt, B. (2020). No Association Between the Home Math Environment and Numerical and Patterning Skills in a Large and Diverse Sample of 5- to 6-year-olds. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.547626

Dearing, E., Casey, B. M., Ganley, C. M., Tillinger, M., Laski, E., & Montecillo, C. (2012). Young girls' arithmetic and spatial skills: The distal and proximal roles of family socioeconomics and home learning experiences. *Early Childhood Research Quarterly*, *27*(3), 458–470. https://doi.org/10.1016/J.ECRESQ.2012.01.002

DeFlorio, L., & Beliakoff, A. (2015). Socioeconomic Status and Preschoolers' Mathematical Knowledge: The Contribution of Home Activities and Parent Beliefs. *Early Education and Development*, *26*(3), 319–341. https://doi.org/10.1080/10409289.2015.968239

del Río, M. F., Susperreguy, M. I., Strasser, K., & Salinas, V. (2017). Distinct Influences of Mothers and Fathers on Kindergartners' Numeracy Performance: The Role of Math Anxiety, Home Numeracy Practices, and Numeracy Expectations. *Early Education and Development*, *28*(8). https://doi.org/10.1080/10409289.2017.1331662

Department for Business Innovation & Skills. (2012). *Skills for Life Survey: A Survey of Literacy, Numeracy and ICT Levels in England*.

Department for Education. (2010). *Achievement of Children in the Early Years Foundation Stage Profile*.

Department for Education. (2014a). *Statistical First Release Early Years Foundation Stage Profile results in England, 2013/14*.

Department for Education. (2014b). *The economic value of key intermediate qualifications: estimating the returns and lifetime productivity gains to GCSEs, A levels and apprenticeships*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/387160/RR398A_-_Economic_Value_of_Key_Qualifications.pdf

Department for Education. (2019). *Early years foundation stage profile results in England 2019* (Issue October 2019). https://www.gov.uk/government/statistics/early-years-foundation-stage-profile-results-2017-to-2018

Department for Education. (2021a). *Schools, pupils and their characteristics*.

Department for Education. (2021b). *Statutory framework for the early years foundation stage.*

Department for Work and Pensions. (2019). *Households Below Average Income: An analysis of the UK income distribution: 1994/95-2014/15.*

Department of Education. (2019). *Participation rates in Higher Education 2006/07 - 2017/18* (Vol. 2018, Issue September).

Devine, R. T., Bignardi, G., & Hughes, C. (2016). Executive Function Mediates the Relations between Parental Behaviors and Children's Early Academic Ability. *Frontiers in Psychology*, *7*, 1902. https://doi.org/10.3389/fpsyg.2016.01902

Diamond, A. (2013). Executive Functions. *Annual Review of Psychology*, *64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

DiPrete, T. A., & Eirich, G. M. (2006). Cumulative Advantage as a Mechanism for Inequality: A Review of Theoretical and Empirical Developments. *Annual Review of Sociology*, *32*(1), 271–297. https://doi.org/10.1146/annurev.soc.32.061604.123127

Dollaghan, C. A., Campbell, T. F., Paradise, J. L., Feldman, H. M., Janosky, J. E., Pitcairn, D. N., & Kurs-Lasky, M. (1999). Maternal education and measures of early speech and language. *Journal of Speech, Language, and Hearing Research*, *42*(6), 1432–1443. https://doi.org/10.1044/jslhr.4206.1432

Dong, Y., Dong, W. Y., Wu, S. X. Y., & Tang, Y. (2020). The effects of home literacy environment on children's reading comprehension development: A meta-analysis. *Educational Sciences: Theory and Practice*, *20*(2), 63–82. https://doi.org/10.12738/jestp.2020.2.005

Dowker, A. (2008). Individual differences in numerical abilities in preschoolers. *Developmental Science*, *11*(5), 650–654. https://doi.org/10.1111/j.1467-7687.2008.00713.x

Dowker, A. (2021). Home Numeracy and Preschool Children's Mathematical Development: Expanding Home Numeracy Models to Include Parental Attitudes and Emotions. *Frontiers in Education*, *6*. https://doi.org/10.3389/feduc.2021.575664

Duff, F. J., Reen, G., Plunkett, K., & Nation, K. (2015). Do infant vocabulary skills predict school-age language and literacy outcomes? *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *56*(8), 848–856. https://doi.org/10.1111/jcpp.12378

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., Sexton, H., Duckworth, K., & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology*, *43*(6), 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428

Duncan, G. J., & Magnuson, K. (2012). Socioeconomic status and cognitive functioning: moving from correlation to causation. *Wiley Interdisciplinary Reviews: Cognitive Science*, *3*(3), 377–386. https://doi.org/10.1002/wcs.1176

Dunn, L. M., Dunn, Leota. M., Whetton, C., & Burley, Juliet. (1997). *British Picture Vocabulary Scale* (2nd ed.). NFER-Nelson. https://www.researchconnections.org/childcare/resources/7656

Dunst, C. J., Hamby, D. W., Wilkie, H., & Dunst, K. S. (2017). *Meta-Analysis of the Relationship Between Home and Family Experiences and Young Children's Early Numeracy Learning* (pp. 105–125). Springer, Singapore. https://doi.org/10.1007/978-981-10-2553-2_7

Educational Endowment Foundation. (2017). *The Attainment Gap*. https://educationendowmentfoundation.org.uk/public/files/Annual_Reports/EEF_Attainment_Gap_Report_2018_-_print.pdf

Ellefson, M. R., Zachariou, A., Ng, F. F.-Y., Wang, Q., & Hughes, C. (2020). Do executive functions mediate the link between socioeconomic status and numeracy skills? A cross-site comparison of Hong Kong and the United Kingdom. *Journal of Experimental Child Psychology*, *194*, 104734. https://doi.org/10.1016/j.jecp.2019.104734

Elliott, L. (2020). Sources of heterogeneity in the home learning environments of socioeconomically disadvantaged families. *Journal of Applied Developmental Psychology*, *70*. https://doi.org/10.1016/j.appdev.2020.101190

Elliott, L., & Bachman, H. J. (2018a). How Do Parents Foster Young Children's Math Skills? *Child Development Perspectives*, *12*(1), 16–21. https://doi.org/10.1111/cdep.12249

Elliott, L., & Bachman, H. J. (2018b). Parents' educational beliefs and children's early academics: Examining the role of SES. *Children and Youth Services Review*, *91*, 11–21. https://doi.org/10.1016/J.CHILDYOUTH.2018.05.022

Elliott, L., & Bachman, H. J. (2018c). SES disparities in early math abilities: The contributions of parents' math cognitions, practices to support math, and math talk. *Developmental Review*, *49*, 1–15. https://doi.org/10.1016/J.DR.2018.08.001

Elliott, L., Bachman, H. J., & Henry, D. A. (2020). Why and How Parents Promote Math Learning with their Young Children: A Mixed-Methods Investigation. *Parenting*, *20*(2), 108–140. https://doi.org/10.1080/15295192.2019.1694830

Ellis, A. (2020). *The Role of Classroom Instruction in the Development of Early Number Skills* [doctoral thesis]. University of Michigan.

Ellis, A., Ahmed, S. F., Zeytinoglu, S., Isbell, E., Calkins, S. D., Leerkes, E. M., Grammer, J. K., Gehring, W. J., Morrison, F. J., & Davis-Kean, P. E. (2021). Reciprocal associations between executive function and academic achievement: A conceptual replication of Schmitt et al. (2017). *Journal of Numerical Cognition*, *7*(3), 453–472. https://doi.org/10.5964/jnc.7047

European Commission. (2018). *The European Qualifications Framework*. https://doi.org/10.7135/upo9780857286581.008

Every Child a Chance Trust. (2009). *The long term costs of numeracy difficulties*.

Fairley, L., Cabieses, B., Small, N., Petherick, E. S., Lawlor, D. A., Pickett, K. E., & Wright, J. (2014). Using latent class analysis to develop a model of the relationship between socioeconomic position and ethnicity: cross-sectional analyses from a multi-ethnic birth cohort study. *BMC Public Health*, *14*(1), 835. https://doi.org/10.1186/1471-2458-14-835

Fanari, R., Meloni, C., & Massidda, D. (2019). Visual and Spatial Working Memory Abilities Predict Early Math Skills: A Longitudinal Study. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.02460

Farkas, G., & Beron, K. (2004). The detailed age trajectory of oral vocabulary knowledge: Differences by class and race. *Social Science Research*, *33*(3), 464–497. https://doi.org/10.1016/j.ssresearch.2003.08.001

Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: Object files versus analog magnitudes. *Psychological Science*, *13*(2), 150–156. https://doi.org/10.1111/1467-9280.00427

Fenson, L., Marchman, V. A., Thal, D., Dale, P. S., Reznick, J. S., & Bates, E. (2007). *MacArthur-Bates Communicative Development Inventories: User's guide and technical manual* (2nd ed.). Brookes Publishing.

Fernald, A., Marchman, V. A., & Weisleder, A. (2013). SES differences in language processing skill and vocabulary are evident at 18 months. *Developmental Science*, *16*(2), 234–248. https://doi.org/10.1111/desc.12019

Finkel, D., Reynolds, C. A., McArdle, J. J., & Pedersen, N. L. (2005). The longitudinal relationship between processing speed and cognitive ability: Genetic and environmental influences. *Behavior Genetics*, *35*(5), 535–549. https://doi.org/10.1007/s10519-005-3281-5

Fitzpatrick, C., McKinnon, R. D., Blair, C. B., & Willoughby, M. T. (2014). Do preschool executive function skills explain the school readiness gap between advantaged and disadvantaged children? *Learning and Instruction*, *30*, 25–31. https://doi.org/10.1016/j.learninstruc.2013.11.003

Foster, M. E., Eplin, P., & Smith, S. A. (n.d.). *The Home Numeracy and Home Literacy Environment, Verbal Ability, and Executive Functioning: Describing Early Numeracy and Literacy* [poster presentation].

Fu, R., Gartlehner, G., Grant, M., Shamliyan, T., Sedrakyan, A., Wilt, T. J., Griffith, L., Oremus, M., Raina, P., Ismaila, A., Santaguida, P., Lau, J., & Trikalinos, T. A. (2010). Conducting Quantitative Synthesis When Comparing Medical Interventions: AHRQ and the Effective Health Care Program. In *Methods Guide for Effectiveness and Comparative Effectiveness Reviews*. Agency for Healthcare Research and Quality (US). www.effectivehealthcare.ahrq.gov.

Fusarelli, L. D. (2015). Child Welfare, Education, Inequality, and Social Policy in Comparative Perspective. *Peabody Journal of Education*, *90*(5), 677–690. https://doi.org/10.1080/0161956X.2015.1087779

Galindo, C., & Sonnenschein, S. (2015). Decreasing the SES math achievement gap: Initial math proficiency and home learning environments. *Contemporary Educational Psychology*, *43*, 25–38. https://doi.org/10.1016/j.cedpsych.2015.08.003

Galobardes, B., Shaw, M., Lawlor, D. A., Lynch, J. W., & Davey Smith, G. (2006). Indicators of socioeconomic position (part 1). *Journal of Epidemiology & Community Health*, *60*(1), 7–12. https://doi.org/10.1136/jech.2004.023531

Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive Function in Preschoolers: A Review Using an Integrative Framework. *Psychological Bulletin*, *134*(1), 31–60. https://doi.org/10.1037/0033-2909.134.1.31

Geary, D. C. (2004). Mathematics and Learning Disabilities. *Journal of Learning Disabilities*, *37*(1), 4–15. https://doi.org/10.1177/00222194040370010201

Gelman, R., & Gallistel, C. R. (1978). *The Child's Understanding of Number.* Harvard University Press.

Gilmore, C., Göbel, S. M., & Inglis, M. (2018). *An Introduction to Mathematical Cognition* (Vol. 1). Routledge.

Gilmore, C., Keeble, S., Richardson, S., & Cragg, L. (2015). The role of cognitive inhibition in different components of arithmetic. *ZDM*, *47*(5), 771–782. https://doi.org/10.1007/s11858-014-0659-y

Ginsbery, H. P., & Baroody, A. J. (2003). *Test of early mathematics ability* (3rd ed.).

Grammer, J. K., Coffman, J. L., Ornstein, P. A., & Morrison, F. J. (2013). Change over Time: Conducting Longitudinal Studies of Children's Cognitive Development. *Journal of Cognitive Development*, *14*(4), 515–528. https://doi.org/10.1080/15248372.2013.833925.Change

Gunderson, E. A., & Levine, S. C. (2011). Some types of parent number talk count more than others: relations between parents' input and children's cardinal-number knowledge. *Developmental Science*, *14*(5), 1021–1032. https://doi.org/10.1111/j.1467-7687.2011.01050.x

Guryan, J., Hurst, E., & Kearney, M. (2008). Parental education and parental time with children. *Journal of Economic Perspectives*, *22*(3), 23–46. https://doi.org/10.1257/jep.22.3.23

Hackman, D. A., Betancourt, L. M., Gallop, R., Romer, D., Brodsky, N. L., Hurt, H., & Farah, M. J. (2014). Mapping the Trajectory of Socioeconomic Disparity in Working Memory: Parental and Neighborhood Factors. *Child Development*, *85*(4), 1433–1445. https://doi.org/10.1111/cdev.12242

Hackman, D. A., & Farah, M. J. (2009). Socioeconomic status and the developing brain. *Trends in Cognitive Sciences*, *13*(2), 65–73. https://doi.org/10.1016/J.TICS.2008.11.003

Hackman, D. A., Gallop, R., Evans, G. W., & Farah, M. J. (2015). Socioeconomic status and executive function: Developmental trajectories and mediation. *Developmental Science*, *18*(5), 686–702. https://doi.org/10.1111/desc.12246

Hammond, S. I., Müller, U., Carpendale, J. I. M., Bibok, M. B., & Liebermann-Finestone, D. P. (2012). The effects of parental scaffolding on preschoolers' executive function. *Developmental Psychology*, *48*(1), 271–281. https://doi.org/10.1037/a0025519

Hart, B., & Risley, T. R. (1995). Meaningful differences in the everyday experience of young American children. In *Meaningful differences in the everyday experience of young American children.* Paul H Brookes Publishing.

Head, M. L., Holman, L., Lanfear, R., Kahn, A. T., & Jennions, M. D. (2015). The Extent and Consequences of P-Hacking in Science. *PLoS Biology*, *13*(3). https://doi.org/10.1371/journal.pbio.1002106

Higgins, J. P. T., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*, *21*(11), 1539–1558. https://doi.org/10.1002/sim.1186

Hirsh-Pasek, K., Adamson, L. B., Bakeman, R., Owen, M. T., Golinkoff, R. M., Pace, A., Yust, P. K. S., & Suma, K. (2015). The Contribution of Early Communication Quality to Low-Income Children's Language Success. *Psychological Science*, *26*(7), 1071–1083. https://doi.org/10.1177/0956797615581493

Hoff, E. (2003). The Specificity of Environmental Influence: Socioeconomic Status Affects Early Vocabulary Development Via Maternal Speech. *Child Development*, *74*(5), 1368–1378. https://doi.org/10.1111/1467-8624.00612

Huang, Q., Zhang, X., Liu, Y., Yang, W., & Song, Z. (2017a). The contribution of parent-child numeracy activities to young Chinese children's mathematical ability. *British Journal of Educational Psychology*, *87*(3), 328–344. https://doi.org/10.1111/bjep.12152

Huang, Q., Zhang, X., Liu, Y., Yang, W., & Song, Z. (2017b). The contribution of parent–child numeracy activities to young Chinese children's mathematical ability. *British Journal of Educational Psychology*, *87*(3), 328–344. https://doi.org/10.1111/bjep.12152

Hughes, C. H., & Ensor, R. A. (2009). How do families help or hinder the emergence of early executive function? *New Directions for Child and Adolescent Development*, *2009*(123), 35–50. https://doi.org/10.1002/cd.234

Huizinga, M., Dolan, C. V., & van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia*, *44*(11), 2017–2036. https://doi.org/10.1016/j.neuropsychologia.2006.01.010

Huntsinger, C. S., Jose, P. E., & Luo, Z. (2016). Parental facilitation of early mathematics and reading skills and knowledge through encouragement of home-based activities. *Early Childhood Research Quarterly*, *37*, 1–15. https://doi.org/10.1016/J.ECRESQ.2016.02.005

Huttenlocher, J., Haight, W., Bryk, A., Seltzer, M., & Lyons, T. (1991). Early Vocabulary Growth: Relation to Language Input and Gender. *Developmental Psychology*, *27*(2), 236–248. https://doi.org/10.1037/0012-1649.27.2.236

Huttenlocher, J., Waterfall, H., Vasilyeva, M., Vevea, J., & Hedges, L. V. (2010). Sources of variability in children's language growth. *Cognitive Psychology*, *61*(4), 343–365. https://doi.org/10.1016/j.cogpsych.2010.08.002.Sources

Jackman, M. R., & Jackman, R. W. (1973). An Interpretation of the Relation Between Objective and Subjective Social Status. *American Sociological Review*, *38*(5), 569. https://doi.org/10.2307/2094408

Jackson, D., & Turner, R. (2017). Power analysis for random-effects meta-analysis. *Research Synthesis Methods*, *8*(3), 290–302. https://doi.org/10.1002/jrsm.1240

James-Brabham, E., Loveridge, T., Sella, F., Wakeling, P., Carroll, J. C., & Blakey, E. (2021a). *How do Socioeconomic Attainment Gaps in Early Maths Ability Arise? Study 2.*

James-Brabham, Loveridge, T., Sella, F., Wakeling, P., Carroll, J. C., & Blakey, E. (2021b). *How do Socioeconomic Attainment Gaps in Early Maths Ability Arise? Study 1.*

Jerrim, J., & Vignoles, A. (2013). Social mobility, regression to the mean and the cognitive development of high ability children from disadvantaged homes. *Journal of the Royal*

Statistical Society: Series A (Statistics in Society), *176*(4), 887–906. https://doi.org/10.1111/j.1467-985X.2012.01072.x

Jose, P. E. (2016). The Merits of Using Longitudinal Mediation. *Educational Psychologist*, *51*(3–4), 331–341. https://doi.org/10.1080/00461520.2016.1207175

Kalil, A., Ryan, R., & Corey, M. (2012). Diverging Destinies: Maternal Education and the Developmental Gradient in Time with Children. *Demography*, *49*(4), 1361–1383. https://doi.org/10.1007/s13524-012-0129-5.Diverging

Kaplan, G. A., Shema, S. J., & Leite, C. M. A. (2008). Socioeconomic determinants of psychological well-being: the role of income, income change, and income sources during the course of 29 years. *Annals of Epidemiology*, *18*(7), 531–537. https://doi.org/10.1016/j.annepidem.2008.03.006

Keating, M., Harmon, T., & Arnold, D. H. (2021). Relations between parental math beliefs and emergent math skills among preschoolers from low-income households. *Early Child Development and Care*, 1–9. https://doi.org/10.1080/03004430.2021.1881076

Khanolainen, D., Psyridou, M., Silinskas, G., Lerkkanen, M. K., Niemi, P., Poikkeus, A. M., & Torppa, M. (2020). Longitudinal Effects of the Home Learning Environment and Parental Difficulties on Reading and Math Development Across Grades 1–9. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.577981

King, Y. A., Duncan, R. J., Posada, G., & Purpura, D. J. (2020). Construct-Specific and Timing-Specific Aspects of the Home Environment for Children’s School Readiness. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.01959

King, Y. A., & Purpura, D. J. (2021). Direct numeracy activities and early math skills: Math language as a mediator. *Early Childhood Research Quarterly*, *54*, 252–259. https://doi.org/10.1016/j.ecresq.2020.09.012

Kleemans, T., Peeters, M., Segers, E., & Verhoeven, L. (2012). Child and home predictors of early numeracy skills in kindergarten. *Early Childhood Research Quarterly*, *27*(3), 471–477. https://doi.org/10.1016/j.ecresq.2011.12.004

Klibanoff, R. S., Levine, S. C., Huttenlocher, J., Vasilyeva, M., & Hedges, L. V. (2006). Preschool children’s mathematical knowledge: The effect of teacher "math talk." *Developmental Psychology*, *42*(1), 59–69. https://doi.org/10.1037/0012-1649.42.1.59

Kwing Cheung, S., Yang, X., May Dulay, K., & McBride, C. (2018). Family and individual variables associated with young Filipino children’s numeracy interest and competence. *British Journal of Developmental Psychology*, *36*, 334–353. https://doi.org/10.1111/bjdp.12222

Lagattuta, K. H., Sayfan, L., & Monsour, M. (2011). A new measure for assessing executive function across a wide age range: Children and adults find happy-sad more difficult than day-night. *Developmental Science*, *14*(3), 481–489. https://doi.org/10.1111/j.1467-7687.2010.00994.x

Lareau, A. (2002). Invisible Inequality: Social Class and Childrearing in Black Families and White Families. *American Sociological Review*, *67*(5), 747. https://doi.org/10.2307/3088916

Larson, K., Russ, S. A., Nelson, B. B., Olson, L. M., & Halfon, N. (2015). Cognitive Ability at Kindergarten Entry and Socioeconomic Status. *Pediatrics*, *135*(2), 440–448. https://doi.org/10.1542/peds.2014-0434

Lawson, G. M., & Farah, M. J. (2017). Executive Function as a Mediator Between SES and Academic Achievement Throughout Childhood. *International Journal of Behavioral Development*, *41*(1), 94–104. https://doi.org/10.1177/0165025415603489

Lawson, G. M., Hook, C. J., & Farah, M. J. (2018). A meta-analysis of the relationship between socioeconomic status and executive function performance among children. *Developmental Science*, *21*(2). https://doi.org/10.1111/desc.12529

Lê, M. L. T., & Noël, M. P. (2020). Transparent number-naming system gives only limited advantage for preschooler's numerical development: Comparisons of Vietnamese and French-speaking children. *PLoS ONE*, *15*(12 December). https://doi.org/10.1371/journal.pone.0243472

Lee, K., Bull, R., & Ho, R. M. H. (2013). Developmental Changes in Executive Functioning. *Child Development*, *84*(6), 1933–1953. https://doi.org/10.1111/cdev.12096

Lefevre, J. (2000). Research on the development of academic skills: Introduction to the special issue on early literacy and early numeracy. *Canadian Journal of Experimental Psychology*, *54*(2), 57–64. https://doi.org/10.1037/h0088185

LeFevre, J. A., Polyzoi, E., Skwarchuk, S. L., Fast, L., & Sowinski, C. (2010). Do home numeracy and literacy practices of Greek and Canadian parents predict the numeracy skills of kindergarten children? *International Journal of Early Years Education*, *18*(1), 55–70. https://doi.org/10.1080/09669761003693926

Lefevre, J., Skwarchuk, S.-L., Smith-Chant, B. L., Fast, L., Kamawar, D., & Bisanz, J. (2009). Home Numeracy Experiences and Children's Math Performance in the Early School Years. *Canadian Journal of Behavioural Science*, *41*(2), 55–66. https://doi.org/10.1037/a0014532

LeFevre, J.-A., Fast, L., Skwarchuk, S.-L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to Mathematics: Longitudinal Predictors of Performance. *Child Development*, *81*(6), 1753–1767. https://doi.org/10.1111/j.1467-8624.2010.01508.x

Lehrl, S., Ebert, S., Blaurock, S., Rossbach, H. G., & Weinert, S. (2020). Long-term and domain-specific relations between the early years home learning environment and students' academic outcomes in secondary school. *School Effectiveness and School Improvement*, *31*(1), 102–124. https://doi.org/10.1080/09243453.2019.1618346

Lehrl, S., Evangelou, M., & Sammons, P. (2020). The home learning environment and its role in shaping children's educational development. *School Effectiveness and School Improvement*, *31*(1), 1–6. https://doi.org/10.1080/09243453.2020.1693487

Lehto, J. E., Juujärvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology*, *21*(1), 59–80. https://doi.org/10.1348/026151003321164627

Lerner, M. D., & Lonigan, C. J. (2014). Executive Function Among Preschool Children: Unitary Versus Distinct Abilities. *Journal of Psychopathology and Behavioral Assessment*, *36*(4), 626–639. https://doi.org/10.1007/s10862-014-9424-3

Light, R. J., & Pillemer, D. B. (1984). *Summing up. The science of reviewing research.* Harvard University Press.

Lin, L., & Chu, H. (2018). Quantifying publication bias in meta-analysis. *Biometrics*, *74*(3), 785–794. https://doi.org/10.1111/biom.12817

Lin, X., Peng, P., & Zeng, J. (2021). Understanding the Relation between Mathematics Vocabulary and Mathematics Performance. *The Elementary School Journal*, *121*(3), 504–540. https://doi.org/10.1086/712504

Linberg, A., Lehrl, S., & Weinert, S. (2020). The Early Years Home Learning Environment – Associations With Parent-Child-Course Attendance and Children's Vocabulary at Age 3. *Frontiers in Psychology*, *11*, 1–13. https://doi.org/10.3389/fpsyg.2020.01425

Liu, Y., Zhang, X., Song, Z., & Yang, W. (2019). The unique role of father–child numeracy activities in number competence of very young Chinese children. *Infant and Child Development*, *28*(4). https://doi.org/10.1002/icd.2135

Lowe, J. R., Erickson, S. J., MacLean, P., Schrader, R., & Fuller, J. (2013). Association of maternal scaffolding to maternal education and cognition in toddlers born preterm and full term. *Acta Paediatrica*, *102*(1), 72–77. https://doi.org/10.1111/apa.12037

Lubin, A., Vidal, J., Lanoë, C., Houdé, O., & Borst, G. (2013). Inhibitory control is needed for the resolution of arithmetic word problems: A developmental negative priming study. *Journal of Educational Psychology*, *105*(3), 701–708. https://doi.org/10.1037/a0032625

Lurie, L. A., Hagen, M. P., McLaughlin, K. A., Sheridan, M. A., Meltzoff, A. N., & Rosen, M. L. (2021). Mechanisms linking socioeconomic status and academic achievement in early childhood: Cognitive stimulation and language. *Cognitive Development*, *58*. https://doi.org/10.1016/j.cogdev.2021.101045

Lyons, I. M., & Beilock, S. L. (2011). Numerical ordering ability mediates the relation between number-sense and arithmetic competence. *Cognition*, *121*(2), 256–261. https://doi.org/10.1016/j.cognition.2011.07.009

Maloney, E. A., Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L. (2015). Intergenerational Effects of Parents' Math Anxiety on Children's Math Achievement and Anxiety. *Psychological Science*, *26*(9), 1480–1488. https://doi.org/10.1177/0956797615592630

Manolitsis, G., Georgiou, G. K., & Tziraki, N. (2013). Examining the effects of home literacy and numeracy environment on early reading and math acquisition. *Early Childhood Research Quarterly*, *28*(4), 692–703. https://doi.org/10.1016/j.ecresq.2013.05.004

Marinova, M., Reynvoet, B., & Sasanguie, D. (2021). Mapping between number notations in kindergarten and the role of home numeracy. *Cognitive Development*, *57*, 101002. https://doi.org/10.1016/j.cogdev.2020.101002

Marulis, L. M., & Neuman, S. B. (2010). The effects of vocabulary intervention on young Children's word learning: A meta-analysis. *Review of Educational Research*, *80*(3), 300–335. https://doi.org/10.3102/0034654310377087

McCormack, T., Simms, V., McGourty, J., & Beckers, T. (2013). Blocking in children's causal learning depends on working memory and reasoning abilities. *Journal of Experimental Child Psychology*, *115*(3), 562–569. https://doi.org/10.1016/j.jecp.2012.11.016

McCormick, M. P., Weissman, A. K., Weiland, C., Hsueh, J., Sachs, J., & Snow, C. (2020). Time well spent: Home learning activities and gains in children's academic skills in the prekindergarten year. *Developmental Psychology*, *56*(4), 710–726. https://doi.org/10.1037/dev0000891

McEwen, B. S., & Gianaros, P. J. (2010). Central role of the brain in stress and adaptation: Links to socioeconomic status, health, and disease. *Annals of the New York Academy of Sciences*, *1186*(1), 190–222. https://doi.org/10.1111/j.1749-6632.2009.05331.x

McGillion, M., Pine, J. M., Herbert, J. S., & Matthews, D. (2017). A randomised controlled trial to test the effect of promoting caregiver contingent talk on language development in infants from diverse socioeconomic status backgrounds. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *58*(10), 1122–1131. https://doi.org/10.1111/jcpp.12725

Meins, E. (1997). Security of attachment and maternal tutoring strategies: Interaction within the zone of proximal development. *British Journal of Developmental Psychology*, *15*(2), 129–144. https://doi.org/10.1111/j.2044-835X.1997.tb00730.x

Melhuish, E. C., Phan, M. B., Sylva, K., Sammons, P., Siraj-Blatchford, I., & Taggart, B. (2008). Effects of the Home Learning Environment and Preschool Center Experience upon Literacy and Numeracy Development in Early Primary School. *Journal of Social Issues*, *64*(1), 95–114. https://doi.org/10.1111/j.1540-4560.2008.00550.x

Meyer, Lois. M. (2000). Barriers to Meaningful Instruction for English Learners. *Theory into Practice*, *39*(4), 211–219. https://doi.org/10.1207/s15430421tip3904

Miller, M. R., Giesbrecht, G. F., Müller, U., McInerney, R. J., & Kerns, K. A. (2012). A Latent Variable Approach to Determining the Structure of Executive Function in Preschool Children. *Journal of Cognition and Development*, *13*(3), 395–423. https://doi.org/10.1080/15248372.2011.585478

Ministry of Housing Communities and Local Government. (2019). The English indices of deprivation 2019. *Ministry of Housing, Communities & Local Government*, *2019*. https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019

Missall, K., Hojnoski, R. L., Caskie, G. I. L., & Repasky, P. (2015). Home Numeracy Environments of Preschoolers: Examining Relations Among Mathematical Activities, Parent Mathematical Beliefs, and Early Mathematical Skills. *Early Education and Development*, *26*(3), 356–376. https://doi.org/10.1080/10409289.2015.968243

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The Unity and Diversity of Executive Functions and Their Contributions to Complex "Frontal Lobe" Tasks: A Latent Variable Analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Montgomery, D. E., & Koeltzow, T. E. (2010). A review of the day–night task: The Stroop paradigm and interference control in young children. *Developmental Review*, *30*(3), 308–330. https://doi.org/10.1016/j.dr.2010.07.001

Morisset, C. E., Barnard, K. E., Greenberg, M. T., Booth, C. L., & Spieker, S. J. (1990). Environmental influences on early language development: The context of social risk. *Development and Psychopathology*, *2*(2), 127–149. https://doi.org/10.1017/S0954579400000663

Mulder, H., Verhagen, J., van der Ven, S. H. G., Slot, P. L., & Leseman, P. P. M. (2017). Early Executive Function at Age Two Predicts Emergent Mathematics and Literacy at Age Five. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.01706

Müller, U., Liebermann-Finestone, D. P., Carpendale, J. I. M., Hammond, S. I., & Bibok, M. B. (2012). Knowing minds, controlling actions: The developmental relations between theory of mind and executive function from 2 to 4years of age. *Journal of Experimental Child Psychology*, *111*(2), 331–348. https://doi.org/10.1016/j.jecp.2011.08.014

Mutaf Yildiz, B., Sasanguie, D., de Smedt, B., & Reynvoet, B. (2018). Investigating the relationship between two home numeracy measures: A questionnaire and observations during Lego building and book reading. *British Journal of Developmental Psychology*, *36*(2), 354–370. https://doi.org/10.1111/bjdp.12235

Mutaf Yıldız, B., Sasanguie, D., de Smedt, B., & Reynvoet, B. (2018). Frequency of Home Numeracy Activities Is Differentially Related to Basic Number Processing and Calculation Skills in Kindergartners. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.00340

Mutaf-Yıldız, B., Sasanguie, D., de Smedt, B., & Reynvoet, B. (2020). Probing the Relationship Between Home Numeracy and Children's Mathematical Skills: A Systematic Review. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.02074

Napoli, A., & Purpura, D. (2021). *A Text Message-based Home Numeracy Intervention for Parents of Preschoolers*.

Napoli, A. R., Korucu, I., Lin, J., Schmitt, S. A., & Purpura, D. J. (2021). Characteristics Related to Parent-Child Literacy and Numeracy Practices in Preschool. *Frontiers in Education*, *6*. https://doi.org/10.3389/feduc.2021.535832

Napoli, A. R., & Purpura, D. J. (2018). The home literacy and numeracy environment in preschool: Cross-domain relations of parent–child practices and child outcomes. *Journal of Experimental Child Psychology*, *166*, 581–603. https://doi.org/10.1016/j.jecp.2017.10.002

National Literacy Trust. (2018). *Improving the home learning environment: A behaviour change approach*.

National Numeracy. (2015). *Numeracy for Health*. https://www.nationalnumeracy.org.uk/sites/default/files/numeracy_for_health_full.pdf

National Research Council. (2009). *Mathematics Learning in Early Childhood: Paths Toward Excellence and Equity*.

Negen, J., & Sarnecka, W. B. (2012). Number-Concept Acquisition and General Vocabulary Development. *Child Development*, *83*(6), 2019–2027. https://doi.org/10.1038/jid.2014.371

Niklas, F., Annac, E., & Wirth, A. (2020a). *Data from the German Learning4Kids study: cohort 1*.

Niklas, F., Annac, E., & Wirth, A. (2020b). *Data from the German Learning4Kids study: cohort 2*.

Niklas, F., Cohrssen, C., & Tayler, C. (2016). Parents supporting learning: a non-intensive intervention supporting literacy and numeracy in the home learning environment. *International Journal of Early Years Education*, *24*(2), 121–142. https://doi.org/10.1080/09669760.2016.1155147

Niklas, F., & Schneider, W. (2013). Home Literacy Environment and the beginning of reading and spelling. *Contemporary Educational Psychology*, *38*(1), 40–50. https://doi.org/10.1016/J.CEDPSYCH.2012.10.001

Niklas, F., & Schneider, W. (2014). Casting the die before the die is cast: the importance of the home numeracy environment for preschool children. *European Journal of Psychology of Education*, *29*(3), 327–345. https://doi.org/10.1007/s10212-013-0201-6

Niklas, F., & Schneider, W. (2017). *Intervention in the Home Literacy Environment and Kindergarten Children's Vocabulary and Phonological Awareness*.

OECD. (2019). *Income inequality (indicator).* https://doi.org/10.1787/459aa7f1-en

Office for National Statistics. (2014). *Intergenerational transmission of disadvantage in the UK & EU.* http://webarchive.nationalarchives.gov.uk/20160105214416/http://www.ons.gov.uk/ons/rel/household-income/intergenerational-transmission-of-poverty-in-the-uk---eu/2014/blank.html

Oğul, İ. G., & Arnas, Y. Aktaş. (2021). Role of home mathematics activities and mothers' maths talk in predicting children's maths talk and early maths skills. *European Early Childhood Education Research Journal*, *29*(4), 501–518. https://doi.org/10.1080/1350293X.2020.1858128

O'Laughlin, K. D., Martin, M. J., & Ferrer, E. (2018). Cross-Sectional Analysis of Longitudinal Mediation Processes. *Multivariate Behavioral Research*, *53*(3), 375–402. https://doi.org/10.1080/00273171.2018.1454822

Olson, R. K., Keenan, J. M., Byrne, B., Samuelsson, S., Coventry, W. L., Corley, R., Wadsworth, S. J., Willcutt, E. G., DeFries, J. C., Pennington, B. F., & Hulslander, J. (2011). Genetic and Environmental Influences on Vocabulary and Reading Development. *Scientific Studies of Reading*, *15*(1), 26–46. https://doi.org/10.1080/10888438.2011.536128

Organisation for Economic Co-operation and Development. (2013). *OECD Skills Outlook 2013*. OECD. https://doi.org/10.1787/9789264204256-en

Organisation for Economic Co-operation and Development. (2019). How do Early Childhood Education Systems Differ Around the World? In *Education at a Glance 2019* . https://doi.org/10.1787/f8d7880d-en

Östergren, R., & Träff, U. (2013). Early number knowledge and cognitive ability affect early arithmetic ability. *Journal of Experimental Child Psychology*, *115*, 405–421. https://doi.org/10.1016/j.jecp.2013.03.007

Pace, A., Luo, R., Hirsh-Pasek, K., & Golinkoff, R. M. (2017). Identifying pathways between socioeconomic status and language development. *Annual Review of Linguistics*, *3*, 285–308. https://doi.org/10.1146/annurev-linguistics-011516-034226

Pan, Y., Yang, Q., Li, Y., Liu, L., & Liu, S. (2018). Effects of family socioeconomic status on home math activities in urban China: The role of parental beliefs. *Children and Youth Services Review*, *93*, 60–68. https://doi.org/10.1016/J.CHILDYOUTH.2018.07.006

Pardo, J. R., Bax, M. R., González, A. J., & Herrera, R. (2020). Home numeracy activities in relation to basic number processing in kindergartners. *Revista de Educación*, *389*. https://doi.org/10.4438/1988-592X-RE-2020-389-454J

Peng, P., Namkung, J., Barnes, M., & Sun, C. (2016). A meta-analysis of mathematics and working memory: Moderating effects of working memory domain, type of mathematics skill, and sample characteristics. *Journal of Educational Psychology*, *108*(4), 455–473. https://doi.org/10.1037/edu0000079

Phillips, B. M., & Lonigan, C. J. (2009). Variations in the Home Literacy Environment of Preschool Children: A Cluster Analytic Approach. *Scientific Studies of Reading*, *13*(2), 146–174. https://doi.org/10.1080/10888430902769533

Pickett, K. E., & Wilkinson, R. G. (2015). Income inequality and health: A causal review. *Social Science & Medicine*, *128*, 316–326. https://doi.org/10.1016/J.SOCSCIMED.2014.12.031

Prather, R. W., & Alibali, M. W. (2009). The development of arithmetic principle knowledge: How do we know what learners know? *Developmental Review*, *29*(4), 221–248. https://doi.org/10.1016/j.dr.2009.09.001

Preacher, K. J., & Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior Research Methods*, *40*(3), 879–891. https://doi.org/10.3758/BRM.40.3.879

Psaki, S. R., Seidman, J. C., Miller, M., Gottlieb, M., Bhutta, Z. A., Ahmed, T., Ahmed, A. S., Bessong, P., John, S. M., Kang, G., Kosek, M., Lima, A., Shrestha, P., Svensen, E., & Checkley, W. (2014). Measuring socioeconomic status in multicountry studies: results from the eight-country MAL-ED study. *Population Health Metrics*, *12*(1), 8. https://doi.org/10.1186/1478-7954-12-8

Purpura, D. J., & Ganley, C. M. (2014). Working memory and language: Skill-specific or domain-general relations to mathematics? *Journal of Experimental Child Psychology*, *122*, 104–121. https://doi.org/10.1016/j.jecp.2013.12.009

Purpura, D. J., Hume, L. E., Sims, D. M., & Lonigan, C. J. (2011). Early literacy and early numeracy: The value of including early literacy skills in the prediction of numeracy development. *Journal of Experimental Child Psychology*, *110*(4), 647–658. https://doi.org/10.1016/J.JECP.2011.07.004

Purpura, D. J., King, Y. A., Rolan, E., Hornburg, C. B., Schmitt, S. A., Hart, S. A., & Ganley, C. M. (2020). Examining the Factor Structure of the Home Mathematics Environment to Delineate Its Role in Predicting Preschool Numeracy, Mathematical Language, and Spatial Skills. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.01925

Purpura, D. J., & Reid, E. E. (2016). Mathematics and language: Individual and group differences in mathematical language skills in young children. *Early Childhood Research Quarterly*, *36*, 259–268. https://doi.org/10.1016/j.ecresq.2015.12.020

Raghubar, K. P., & Barnes, M. A. (2017). Early numeracy skills in preschool-aged children: a review of neurocognitive findings and implications for assessment and intervention. *The Clinical Neuropsychologist*, *31*(2), 329–351. https://doi.org/10.1080/13854046.2016.1259387

Raghubar, K. P., Barnes, M. A., & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learning and Individual Differences*, *20*(2), 110–122. https://doi.org/10.1016/J.LINDIF.2009.10.005

Ramani, G. B., Rowe, M. L., Eason, S. H., & Leech, K. A. (2015). Math talk during informal learning activities in Head Start families. *Cognitive Development*, *35*, 15–33. https://doi.org/10.1016/J.COGDEV.2014.11.002

Raver, C. C., Blair, C., & Willoughby, M. (2013). Poverty as a predictor of 4-year-olds' executive function: new perspectives on models of differential susceptibility. *Developmental Psychology*, *49*(2), 292–304. https://doi.org/10.1037/a0028343

Ribner, A., Harvey, E., Gervais, R., & Fitzpatrick, C. (2019). Explaining school entry math and reading achievement in Canadian children using the Opportunity-Propensity framework. *Learning and Instruction*, *59*, 65–75. https://doi.org/10.1016/j.learninstruc.2018.10.003

Ricketts, J., Nation, K., & Bishop, D. V. M. (2007). Vocabulary is important for some, but not all reading skills. *Scientific Studies of Reading*, *11*(3), 235–257. https://doi.org/10.1080/10888430701344306

Ritchie, S. J., & Bates, T. C. (2013). Enduring Links From Childhood Mathematics and Reading Achievement to Adult Socioeconomic Status. *Psychological Science*, *24*(7), 1301–1308. https://doi.org/10.1177/0956797612466268

Roberts, N., & Danechi, S. (2022). *Coronavirus and schools*.

Rodriguez, E. T., Tamis-LeMonda, C. S., Spellmann, M. E., Pan, B. A., Raikes, H., Lugo-Gil, J., & Luze, G. (2009). The formative role of home literacy experiences across the first three years of life in children from low-income families. *Journal of Applied Developmental Psychology*, *30*(6), 677–694. https://doi.org/10.1016/j.appdev.2009.01.003

Rose, S., Badr, K., Fletcher, L., Paxman, T., Lord, P., Rutt, S., Styles, B., & Twist, L. (2021). *Impact of School Closures and subsequent support strategies on attainment and socio-emotional wellbeing in Key Stage 1*. www.educationendowmentfoundation.org.uk

Rosen, M. L., Amso, D., & McLaughlin, K. A. (2019). The role of the visual association cortex in scaffolding prefrontal cortex development: A novel mechanism linking socioeconomic status and executive function. *Developmental Cognitive Neuroscience*, *39*. https://doi.org/10.1016/j.dcn.2019.100699

Rosen, M. L., Hagen, M. P., Lurie, L. A., Miles, Z. E., Sheridan, M. A., Meltzoff, A. N., & McLaughlin, K. A. (2020). Cognitive Stimulation as a Mechanism Linking Socioeconomic Status With Executive Function: A Longitudinal Investigation. *Child Development*, *91*(4), e762–e779. https://doi.org/10.1111/cdev.13315

Rosenthal, R. (1979). The file drawer problem and tolerance for null results. *Psychological Bulletin*, *86*(3), 638–641. https://doi.org/10.1037/0033-2909.86.3.638

Roubinov, D. S., & Boyce, W. T. (2017). Parenting and SES: relative values or enduring principles? *Current Opinion in Psychology*, *15*, 162–167. https://doi.org/10.1016/j.copsyc.2017.03.001

Rowe, M. L. (2012). A Longitudinal Investigation of the Role of Quantity and Quality of Child-Directed Speech in Vocabulary Development. *Child Development*, *83*(5), 1762–1774. https://doi.org/10.1111/j.1467-8624.2012.01805.x

Rowe, M. L., Raudenbush, S. W., & Goldin-Meadow, S. (2012). The Pace of Vocabulary Growth Helps Predict Later Vocabulary Skill. *Child Development*, *83*(2), 508–525. https://doi.org/10.1111/j.1467-8624.2011.01710.x

Saracho, O. N., & Spodek, Bernard. (2008). *Contemporary perspectives on mathematics in early childhood education*.

Sarnecka, B. W. (2021). Learning to represent exact numbers. *Synthese*, *198*, 1001–1018. https://doi.org/10.1007/s11229-015-0854-6

Save the Children. (2016). *Read on Get on: A strategy to get England's children reading*.

Saxe, G. B., Guberman, S. R., Gearhart, M., Gelman, R., Massey, C. M., & Rogoff, B. (1987). Social Processes in Early Number Development. *Monographs of the Society for Research in Child Development*, *52*(2), i. https://doi.org/10.2307/1166071

Schmitt, S. A., Geldhof, G. J., Purpura, D. J., Duncan, R., & McClelland, M. M. (2017). Examining the relations between executive function, math, and literacy during the transition to kindergarten: A multi-analytic approach. *Journal of Educational Psychology*, *109*(8), 1120–1140. https://doi.org/10.1037/edu0000193

Segers, E., Kleemans, T., & Verhoeven, L. (2015). Role of Parent Literacy and Numeracy Expectations and Activities in Predicting Early Numeracy Skills. *Mathematical Thinking and Learning*, *17*(2–3), 219–236. https://doi.org/10.1080/10986065.2015.1016819

Sella, F., & Lucangeli, D. (2020). The knowledge of the preceding number reveals a mature understanding of the number sequence. *Cognition*, *194*(August 2019). https://doi.org/10.1016/j.cognition.2019.104104

Sella, F., Lucangeli, D., Cohen Kadosh, R., & Zorzi, M. (2020). Making Sense of Number Words and Arabic Digits: Does Order Count More? *Child Development*, *91*(5), 1456–1470. https://doi.org/10.1111/cdev.13335

Sénéchal, M., & Young, L. (2008). The effect of family literacy interventions on children's acquisition of reading from kindergarten to grade 3: A meta-analytic review. *Review of Educational Research*, *78*(4), 880–907. https://doi.org/10.3102/0034654308320319

Shavers, V. L. (2007). Measurement of Socioeconomic Status in Health Disparities Research. *Journal of the National Medical Association.*, *99*(9), 1013–1023.

Shavlik, M., Davis-Kean, P. E., Schwab, J. F., & Booth, A. E. (2021). Early word-learning skills: A missing link in understanding the vocabulary gap? *Developmental Science*, *24*(2), 1–18. https://doi.org/10.1111/desc.13034

Shonkoff, Jack. P., & Phillips, Deborah. A. (2000). From Neurons to Neighborhoods. In *From Neurons to Neighborhoods: The Science of Early Childhood Development*. National Academies Press. https://doi.org/10.17226/9824

Silinskas, G., di Lonardo, S., Douglas, H., Xu, C., LeFevre, J. A., Garckija, R., Gabrialaviciute, I., & Raiziene, S. (2020). Responsive home numeracy as children progress from kindergarten through Grade 1. *Early Childhood Research Quarterly*, *53*, 484–495. https://doi.org/10.1016/j.ecresq.2020.06.003

Silver, A. M., Elliott, L., Imbeah, A., & Libertus, M. E. (2020). Understanding the unique contributions of home numeracy, inhibitory control, the approximate number system, and spontaneous focusing on number for children's math abilities. *Mathematical Thinking and Learning*, *22*(4), 296–311. https://doi.org/10.1080/10986065.2020.1818469

Silver, A. M., Elliott, L., & Libertus, M. E. (2021). When beliefs matter most: Examining children's math achievement in the context of parental math anxiety. *Journal of Experimental Child Psychology*, *201*. https://doi.org/10.1016/j.jecp.2020.104992

Sirin, S. R. (2005). Socioeconomic Status and Academic Achievement: A Meta-Analytic Review of Research. *Review of Educational Research*, *75*(3), 417–453.

Skwarchuk, S. L. (2009). How do parents support preschoolers' numeracy learning experiences at home? *Early Childhood Education Journal*, *37*(3), 189–197. https://doi.org/10.1007/s10643-009-0340-1

Skwarchuk, S. L., Sowinski, C., & LeFevre, J. A. (2014). Formal and informal home learning activities in relation to children's early numeracy and literacy skills: The development of a home numeracy model. *Journal of Experimental Child Psychology*, *121*(1), 63–84. https://doi.org/10.1016/j.jecp.2013.11.006

Slusser, E., Ribner, A., & Shusterman, A. (2019). Language counts: Early language mediates the relationship between parent education and children's math ability. *Developmental Science*, *22*(3), 1–11. https://doi.org/10.1111/desc.12773

Social Mobility Commission. (2017). *Social mobility in Great Britain: fifth state of the nation report* (Issue November). https://www.gov.uk/government/news/social-mobility-in-great-britain-fifth-state-of-the-nation-report

Social Mobility Commission. (2020). *Monitoring social mobility*.

Song, J. Y., Demuth, K., & Morgan, J. (2018). Input and Processing Factors Affecting Infants' Vocabulary Size at 19 and 25 Months. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.02398

Soni, A., & Kumasi, S. (2015). The Role of Parental Math Attitude in Their Children Math Achievement. *International Journal of Applied Sociology*, *5*(4), 159–163.

Sonnenschein, S., Galindo, C., Metzger, S. R., Thompson, J. A., Huang, H. C., & Lewis, H. (2012). Parents' Beliefs about Children's Math Development and Children's Participation in Math Activities. *Child Development Research*, *2012*, 1–13. https://doi.org/10.1155/2012/851657

Soto-Calvo, E., Simmons, F. R., Adams, A. M., Francis, H. N., & Giofre, D. (2020). Pre-Schoolers' Home Numeracy and Home Literacy Experiences and Their Relationships with Early Number Skills: Evidence from a UK Study. *Early Education and Development*, *31*(1), 113–136. https://doi.org/10.1080/10409289.2019.1617012

Soto-Calvo, E., Simmons, F. R., Adams, A. M., Francis, H. N., Patel, H., & Giofrè, D. (2020). Identifying the preschool home learning experiences that predict early number skills: Evidence from a longitudinal study. *Early Childhood Research Quarterly*, *53*, 314–328. https://doi.org/10.1016/j.ecresq.2020.04.004

Spaepen, E., Gunderson, E. A., Gibson, D., Goldin-Meadow, S., & Levine, S. C. (2018). Meaning before order: Cardinal principle knowledge predicts improvement in understanding the successor principle and exact ordering. *Cognition*, *180*(July), 59–81. https://doi.org/10.1016/j.cognition.2018.06.012

Sperry, D. E., Sperry, L. L., & Miller, P. J. (2019). Reexamining the Verbal Environments of Children From Different Socioeconomic Backgrounds. *Child Development*, *90*(4), 1303–1318. https://doi.org/10.1111/cdev.13072

Starkey, P., & Cooper, R. G. (1995). The development of subitizing in young children. *British Journal of Developmental Psychology*, *13*, 399–420. https://doi.org/10.1111/j.2044-835x.1995.tb00688.x

Starkey, P., & Klein, A. (2008). Sociocultural influences on young children's mathematical knowledge. In *O. N. Saracho & B. Spodek (Eds.), Contemporary perspectives on mathematics in early childhood education* (CT: Inform, pp. 253–276).

Stipek, D., Milburn, S., Clements, D., & Daniels, D. H. (1992). Parents' beliefs about appropriate education for young children. *Journal of Applied Developmental Psychology*, *13*(3), 293–310. https://doi.org/10.1016/0193-3973(92)90034-F

Susperreguy, M. I., di Lonardo Burr, S., Xu, C., Douglas, H., & LeFevre, J. A. (2020). Children's Home Numeracy Environment Predicts Growth of their Early Mathematical Skills in Kindergarten. *Child Development*, *91*(5), 1663–1680. https://doi.org/10.1111/cdev.13353

Susperreguy, M. I., Douglas, H., Xu, C., Molina-Rojas, N., & LeFevre, J. A. (2020a). Expanding the Home Numeracy Model to Chilean children: Relations among parental expectations, attitudes, activities, and children's mathematical outcomes. *Early Childhood Research Quarterly*, *50*, 16–28. https://doi.org/10.1016/j.ecresq.2018.06.010

Susperreguy, M. I., Jiménez Lira, C., Xu, C., LeFevre, J. A., Blanco Vega, H., Benavides Pando, E. V., & Ornelas Contreras, M. (2021). Home Learning Environments of Children in Mexico in Relation to Socioeconomic Status. *Frontiers in Psychology*, *12*. https://doi.org/10.3389/fpsyg.2021.626159

The EndNote Team. (2013). *EndNote* (EndNote X9). Clarivate.

Thompson, R. J., Napoli, A. R., & Purpura, D. J. (2017). Age-related differences in the relation between the home numeracy environment and numeracy skills. *Infant and Child Development*, *26*(5). https://doi.org/10.1002/icd.2019

Trickett, J., Batchelor, S., Brittle, B., Foulkes, M., Pickering, P., Slocombe, S., & Gimore, C. (2021). *The role of parent-led and child-led home numeracy activities in early mathematical skills.*

UCAS. (2016). *Factors associated with predicted and achieved A level attainment. August.*

UNESCO. (2020). *Education: From disruption to recovery*. https://en.unesco.org/covid19/educationresponse

UNESCO. (2022). *Education: From disruption to recovery*. Https://En.Unesco.Org/Covid19/Educationresponse.

Uphoff, E. P., Pickett, K. E., Crouch, S., Small, N., & Wright, J. (2016). Is ethnic density associated with health in a context of social disadvantage? Findings from the Born in Bradford cohort. *Ethnicity & Health*, *21*(2), 196–213. https://doi.org/10.1080/13557858.2015.1047742

Ursache, A., Noble, K. G., & Blair, C. (2015). Socioeconomic Status, Subjective Social Status, and Perceived Stress: Associations with Stress Physiology and Executive Functioning. *Behavioral Medicine*, *41*(3), 145–154. https://doi.org/10.1080/08964289.2015.1024604

van Herwegen, J., & Donlan, C. (n.d.). *Improving Preschoolers' Number Foundations*.

van Steensel, R. (2006). Relations between socio-cultural factors, the home literacy environment and children's literacy development in the first years of primary education. *Journal of Research in Reading*, *29*(4), 367–382. https://doi.org/10.1111/j.1467-9817.2006.00301.x

Vandermaas-Peeler, M., & Pittard, C. (2014). Influences of social context on parent guidance and low-income preschoolers' independent and guided math performance. *Early Child Development and Care*, *184*(4), 500–521. https://doi.org/10.1080/03004430.2013.799155

Vasilyeva, M., Laski, E., Veraksa, A., Weber, L., & Bukhalenkova, D. (2018). Distinct Pathways From Parental Beliefs and Practices to Children's Numeric Skills. *Journal of Cognition and Development*, *19*(4), 345–366. https://doi.org/10.1080/15248372.2018.1483371

Veenman, M. V. J., van Hout-Wolters, B. H. A. M., & Afflerbach, P. (2006). Metacognition and learning: conceptual and methodological considerations. *Metacognition and Learning*, *1*, 3–14. https://doi.org/10.1007/s11409-006-6893-0

Vendetti, C., Kamawar, D., Podjarny, G., & Astle, A. (2015). Measuring Preschoolers' Inhibitory Control Using the Black/White Stroop. *Infant and Child Development*, *24*(6), 587–605. https://doi.org/10.1002/icd.1902

Viechtbauer, W. (2010). Conducting Meta-Analyses in R with the metafor Package. In *JSS Journal of Statistical Software* (Vol. 36). http://www.jstatsoft.org/

von Stumm, S., Rimfeld, K., Dale, P. S., & Plomin, R. (2020). Preschool Verbal and Nonverbal Ability Mediate the Association Between Socioeconomic Status and School Performance. *Child Development*, *91*(3), 705–714. https://doi.org/10.1111/cdev.13364

Vygotsky, L. S. (1978). *Mind in Society: The Development of higher Psychological Processes*. MA: Harvard University Press.

Wagstaff, A., Paci, P., & Joshi, H. (2001). Causes of Inequality in Health: Who are You? Where Do You Live? Or Who Your Parents Were? *World Bank Policy Research Working Paper*, *2713*.

Walker, D., Greenwood, C., Hart, B., & Carta, J. (1994). Prediction of school outcomes based on early language production and socioeconomic factors. *Child Development*, *65*, 606–621. https://doi.org/https://doi.org/1131404

Waters, N., Ahmed, S., Tang, S., & Morrison, F. J. (2021). Pathways from Socioeconomic Status to Early Academic Achievement: The Role of Specific Executive Functions. *Early Childhood Research Quarterly*, *54*(2021), 321–331. https://doi.org/10.1016/j.ecresq.2020.09.008

Watts, T. W., Duncan, G. J., Siegler, R. S., & Davis-Kean, P. E. (2014). What's Past Is Prologue: Relations Between Early Mathematics Knowledge and High School Achievement. *Educational Researcher*, *43*(7), 352–360. https://doi.org/10.3102/0013189X14553660

Wei, W., Li, Y., & Su, H. Y. (2020). Predicting the growth patterns in early mathematics achievement from cognitive and environmental factors among Chinese kindergarten children. *Learning and Individual Differences*, *79*. https://doi.org/10.1016/j.lindif.2020.101841

Wellings, C., Wilkie, N., Stuart, E., & Bull, G. (2013). *Too young to fail a fair start in life*.

Wiebe, S. A., Espy, K. A., & Charak, D. (2008). Using confirmatory factor analysis to understand executive control in preschool children: I. Latent structure. *Developmental Psychology*, *44*(2), 575–587. https://doi.org/10.1037/0012-1649.44.2.575

Wiebe, S. A., Sheffield, T., Nelson, J. M., Clark, C. A. C., Chevalier, N., & Espy, K. A. (2011). The structure of executive function in 3-year-olds. *Journal of Experimental Child Psychology*, *108*(3), 436–452. https://doi.org/10.1016/j.jecp.2010.08.008

Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry*, *17*(2), 89–100. https://doi.org/10.1111/j.1469-7610.1976.tb00381.x

Wynn, K. (1990). Children's understanding of counting. *Cognition*, *36*(2), 155–193. https://doi.org/10.1016/0010-0277(90)90003-3

Wynn, K. (1992). Children's acquisition of the number words and the counting system. *Cognitive Psychology*, *24*(2), 220–251. https://doi.org/10.1016/0010-0285(92)90008-P

Wynn, K. (1995). Origins of Numerical Knowledge. *Mathematical Cognition*, *1*, 35–60.

Xenidou-Dervou, I., Gilmore, C., van der Schoot, M., & van Lieshout, E. C. D. M. (2015). The developmental onset of symbolic approximation: Beyond nonsymbolic representations, the language of numbers matters. *Frontiers in Psychology*, *6*(487). https://doi.org/10.3389/fpsyg.2015.00487

Yeniad, N., Malda, M., Mesman, J., van IJzendoorn, M. H., & Pieper, S. (2013). Shifting ability predicts math and reading performance in children: A meta-analytical study. *Learning and Individual Differences*, *23*, 1–9. https://doi.org/10.1016/J.LINDIF.2012.10.004

Zambrzycka, J., Kotsopoulos, D., Lee, J., & Makosz, S. (2017). In any way, shape, or form? Toddlers' understanding of shapes. *Infant Behavior and Development*, *46*, 144–157. https://doi.org/10.1016/j.infbeh.2016.12.002

Zhang, X., Hu, B. Y., Zou, X., & Ren, L. (2020). Parent–child number application activities predict children's math trajectories from preschool to primary school. *Journal of Educational Psychology*, *112*(8), 1521–1531. https://doi.org/10.1037/edu0000457

Zhou, X., Huang, J., Wang, Z., Wang, B., Zhao, Z., Yang, L., & Yang, Z. (2006). Parent-child interaction and children's number learning. *Early Child Development and Care*, *176*(7), 763–775. https://doi.org/10.1080/03004430500232680

Zippert, E. L., & Ramani, G. B. (2017). Parents' Estimations of Preschoolers' Number Skills Relate to at-Home Number-Related Activity Engagement. *Infant and Child Development*, *26*(2), 1–24. https://doi.org/10.1002/icd.1968

Appendices

Appendix 1: Questionnaire Items

<u>1a) The questionnaire items used in Study One (Chapter Two) to gather demographic information, and to measure frequency of home mathematical activities and parent cognitions about mathematics (i.e., parent beliefs about- and their self-efficacy of- mathematics).</u>

Gender: Male. Female

Your child's date of birth __________________

Your relationship to child __________________

Mother's highest level of education:

- ○ No formal qualifications
- ○ Educated to O' level, CSE, GCSE, or equivalent
- ○ Educated to A' level, or equivalent
- ○ Vocational qualifications / training
- ○ Level 2 certificate, NVQ, or diploma
- ○ Level 3 certificate, NVQ, or diploma
- ○ Level 4 certificate, NVQ, or diploma
- ○ Level 5 certificate, diploma or foundation degree
- ○ Educated to Bachelors degree level or equivalent
- ○ Graduate diploma, PGCE, or equivalent
- ○ Educated to Masters degree level, or equivalent
- ○ Educated to Doctoral degree level
- ○ Other (please give brief details)

In an average week, approximately how often do you and your child engage in the following activities?

	Not at all	Once a week	A few times a week	Every day	Several times per day
Count objects (e.g. you ask how many are there?)	○	○	○	○	○
Play arithmetic games that involve counting, adding or subtracting (e.g. on the computer, iPad or on paper)	○	○	○	○	○
Use concepts such as more/less, full/half-full, short/long	○	○	○	○	○
Recite counting rhymes or songs (e.g. 5 little monkeys)	○	○	○	○	○
Sort objects by colour, size or shape	○	○	○	○	○
Practice writing numbers	○	○	○	○	○
Talk about money when shopping (e.g. which one costs more?)	○	○	○	○	○
Play games involving numbers (e.g. snakes and ladders)	○	○	○	○	○
Refer to time (e.g. talk about the time; child wears a watch; use calendars and dates)	○	○	○	○	○
Play with calculators	○	○	○	○	○

Read storybooks specifically focused on numbers	○	○	○	○	○
Practice reading numbers (e.g. being able to recognize "1" and say it's name "one")	○	○	○	○	○
Connect-the-dot or colour-by-number activities	○	○	○	○	○
Build lego or construction sets	○	○	○	○	○
Play board games with a die or spinner	○	○	○	○	○
Play dominoes	○	○	○	○	○
Play games involving letters (e.g. lotto, boggle, scrabble)	○	○	○	○	○
Play card games	○	○	○	○	○
Weigh, measure, and/or compare quantities (e.g. measure ingredients when cooking)	○	○	○	○	○
Refer to digits ("6") or written numbers ("six") in the environment (e.g. the number on the bus)	○	○	○	○	○
Arrange objects (e.g. from big to small)	○	○	○	○	○
Practice simple sums (e.g. 2+2=4)	○	○	○	○	○

Use educational software or apps, focused on something other than numbers	○	○	○	○	○
Recite numbers in order (e.g. count up to or back from 10)	○	○	○	○	○
Number activity books	○	○	○	○	○

Please read the following, and indicate the degree to which you agree with each statement:

	Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree
Maths is a worthwhile and necessary subject.	○	○	○	○	○
When I was at school, I enjoyed mathematics.	○	○	○	○	○
I am confident in my mathematical abilities.	○	○	○	○	○
I find reading enjoyable.	○	○	○	○	○
A strong mathematical background helps in adult life.	○	○	○	○	○
It is important for preschoolers to develop their mathematical skills.	○	○	○	○	○
It is important for children to be exposed to reading every day.	○	○	○	○	○
I try to incorporate mathematical learning into daily life with my child wherever I can.	○	○	○	○	○
Mathematical skills help with problem-solving in other areas of life.	○	○	○	○	○
I am good at mental calculations.	○	○	○	○	○
Young children learn mathematical skills best through play.	○	○	○	○	○

Mathematical skills are useful in all areas of life.	○	○	○	○	○
I find mathematics activities enjoyable.	○	○	○	○	○
Maths is one of the most important subjects.	○	○	○	○	○
I feel comfortable solving mathematical problems.	○	○	○	○	○
The career path I have chosen in mathematics related.	○	○	○	○	○
It is important for children to be exposed to mathematical concepts every day.	○	○	○	○	○
When I was at school, I was good at Mathematics.	○	○	○	○	○

1b) The questionnaire items used in Study Three (Chapter Four) to gather demographic information, and to measure frequency of home mathematical activities.

Your child's Date of Birth: ……../……../……..

Your child's gender: Male ☐ Female ☐

Your address **and** postcode: …………………………………………………

Which best describes the ethnicity of your child?

(a) White - British	☐
(b) White – another background*	☐
(c) Black - British	☐
(d) Black - Caribbean	☐
(e) Black - African	☐
(f) Black – another background*	☐
(g) Asian - Indian	☐
(h) Asian – Pakistani	☐
(i) Asian - Bangladeshi	☐
(j) Asian – another background*	☐
(k) Chinese	☐
(l) Mixed ethnicity*	☐
(m) Another ethnic group*	☐

*Please give any additional information: …………………

What is your relationship to the child who's taking part in our project?

(a) Mother	☐	(b) Father	☐
(c) Stepmother	☐	(d) Stepfather	☐
(e) Grandparent	☐	(f) Foster parent	☐
(g) Adoptive parent	☐	(h) Other *(please specify)*:	…………………………

Education:

What is your <u>highest</u> education qualification?

(a)	No formal qualifications	☐
(b)	1 or more GCSEs/ O levels/ CSEs (any grades), and/or level 1 diploma/ NVQ/ functional skills	☐
(c)	5 or more GCSEs (grades A*-C)/ 5+ O levels/ 5+ CSEs (grade 1)/ School Certificate, and/or level 2 diploma/ NVQ/ functional skills	☐
(d)	A level/ As level, and/or access to higher education diploma, international baccalaureate diploma/ level 3 diploma/ NVQ	☐
(e)	Certificate of higher education, and/or higher apprenticeship/ HNC/ level 4 diploma/ NVQ	☐
(f)	Foundation Degree, and/or diploma of higher education/ level 5 diploma/ NVQ	☐
(g)	First Degree (e.g. BA, BSc) and/or degree apprenticeship/ graduate diploma/ level 6 diploma/ NVQ	☐
(h)	Master's degree, and/or level 7 diploma/ NVQ/ PGCE/ Postgraduate diploma	☐
(i)	Doctorate (e.g. PhD or DPhil), and/or level 8 diploma	☐

Home Activities

In the past <u>month</u> how often did you and your child work together on the following? This could be part of learning activities, simply part of your daily routine or through technology. <u>*Please circle*</u>

Counting.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Writing out numbers.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Scenario-based number games (e.g. 'if I have two toy cars and I take one away, how many cars do I have').

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Counting on fingers/ hands.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Watching number related or rhyming TV shows (e.g. Number Jacks or Numtums).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Teaching about measurement (e.g. baking, height).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Sticker books.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Sorting shapes.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Playing with jigsaws.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Watch educational programmes (e.g. Dora the Explorer).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Sorting objects by size.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Comparing sets of objects (e.g. brother has more sweets than mum).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Pairing/ matching games.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Playing with building blocks.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Identifying the names of written numbers.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Counting out food, dinner plates, knives, forks.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Creating patterns with objects (e.g. arranging blocks into shapes).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Counting objects (e.g. ducks in bath, blocks, new toys, books).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Teaching about money (e.g. informal (playing shop) or formal (buying sweets)).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Time terminology (e.g. big hand, little hand).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Asking shape related questions (e.g. ‘how many sides does a circle have?’).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Arranging objects by size, shape or colour.

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Singing rhyming songs together (e.g. ‘1, 2 ,3 4, 5 once I caught a fish alive’).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Reading books together that involve numbers (e.g. hungry caterpillar).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Timed games (e.g. hide and seek).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

Everyday activities that involve number (e.g. using money while shopping/ weighing ingredients while cooking).

Activity did not occur	Few times a month	About once a week	Few times a week	Almost daily

1c) The questionnaire items used in Study Four (Chapter Four) to gather demographic information, and to measure frequency of home mathematical activities.

Your Child's Date of Birth: ……../……../……..

Your Child's Gender: M / F (please circle one)

Your Child's Ethnicity ………………………….

Your address and postcode (kept strictly confidential): ……………………………..
Form completed by: ………………………………… (e.g., Mum/Dad/Gran)

Education

For each parent/carer, please select one category, which best describes their highest level of education:

	Mother	Father
No formal qualifications	☐	☐
1-4 GCSEs/O Levels (at any grade) NVQ Level 1 or similar	☐	☐
5+ GCSEs (grades A*-C)/O levels (passes)/NVQ level 2 or similar	☐	☐
1 A Level/ 2-3 AS Levels	☐	☐
2+ A Levels/NVQ Level 3 or similar	☐	☐
University degree/HND/HNC/NVQ Level 4 or 5/similar	☐	☐
Postgraduate degree or similar e.g. (PGCE, PhD, MA etc.)	☐	☐

Home Activities

For this section, please think about the activities your child engages at home. You might have engaged with some of these activities, or not. There is no expectation you would have, we are just interested in the type of activities children do in the home at this age.

In the past month, how often did you and your child engage in the following activities? (tick one option for each activity)

	Activity did not occur	Activity occurred one-three times per month	Activity occurred about once per week	Activity occurred a few times a week (2-4 times)	Activity occurred almost daily
Using number or arithmetic flashcards	☐	☐	☐	☐	☐
Identifying the names of written numbers (i.e. 4)	☐	☐	☐	☐	☐
Counting objects	☐	☐	☐	☐	☐
Sorting things by colour, size or shape	☐	☐	☐	☐	☐
Counting down (10, 9, 8, 7…)	☐	☐	☐	☐	☐
Learning simple sums (i.e. 2 + 2 = 4)	☐	☐	☐	☐	☐

Writing numbers	☐	☐	☐	☐	☐
Talking about money when shopping (e.g. 'which costs more?)	☐	☐	☐	☐	☐
Measuring ingredients when cooking	☐	☐	☐	☐	☐
Being timed or timing the child	☐	☐	☐	☐	☐
Playing with calculators	☐	☐	☐	☐	☐
Making collections of items or objects	☐	☐	☐	☐	☐
'Connect-the-dot' activities	☐	☐	☐	☐	☐
Using calendars and dates	☐	☐	☐	☐	☐
Having your child wear a watch	☐	☐	☐	☐	☐
Using number activity books	☐	☐	☐	☐	☐
Reading story books that contain numbers	☐	☐	☐	☐	☐
Playing board games with die or spinner	☐	☐	☐	☐	☐
Playing card games with numbers	☐	☐	☐	☐	☐
Counting out money	☐	☐	☐	☐	☐
Playing with numeracy/maths computer games or apps	☐	☐	☐	☐	☐

1d) The questionnaire items used in Study Six (Chapter Six) to gather demographic information, and to measure frequency of home mathematical activities, hours spent on home mathematical learning, parent cognitions about mathematics (i.e., parent beliefs about- and their self-efficacy of- mathematics), and difficulties and barriers parents have experienced to home mathematical learning during Covid-19.

Are you a parent or carer of a child aged between three and seven years?

- ◯ Yes, I have one child aged between three and seven years
- ◯ Yes, I have more than one child aged between three and seven years
- ◯ No, I do not have a child aged between three and seven

Please give information for your youngest child aged between three and seven throughout the following questions

General Information about your Child and Family

Your Child's Date of Birth: ________
Your Child's Sex:

- ◯ Male
- ◯ Female
- ◯ Prefer not to say
- ◯ Other, please state ____

Your full postcode:
We use this to extract area information. This information will be kept strictly confidential and deleted after the area information has been extracted.

____

Which best describes the ethnicity of your child?

☐ White-British

☐ White - another background*

☐ Black-British

☐ Black-Caribbean

☐ Black-African

☐ Black - another background*

☐ Asian-Indian

☐ Asian-Pakistani

☐ Asian-Bangladeshi

☐ Asian- another background*

☐ Chinese

☐ Mixed ethnicity*

☐ Another ethnic group

☐ *Please give any additional information

____

Before UK lockdown on 23rd March 2020, did your child attend nursery, school or a childminder?

- ☐ Nursery (part-time)
- ☐ Nursery (full-time)
- ☐ Primary school
- ☐ Child minder
- ☐ My child does not attend nursery
- ☐ My child is home schooled
- ☐ Other, please state ____

Has your child returned to nursery/school/child minder?

- ○ My child has continued to attend nursery/ school/ child minder throughout lock down
- ○ My child has returned to nursery/ school/ child minder since schools have started to reopen to all children
- ○ My child is not yet eligible to return to school
- ○ My child is eligible to return to nursery/school/child minder but has not yet returned
- ○ Other, please state ____

Has a member of your household needed to shield during the COVID-19 lockdown?

- ○ Yes
- ○ No (2)

About You

What is your relationship to the child who's taking part in our project?

- ☐ Mother
- ☐ Father
- ☐ Stepmother
- ☐ Stepfather
- ☐ Grandparent
- ☐ Foster parent
- ☐ Adoptive parent
- ☐ Other (please specify)

____

Are you the primary/main care giver? ***(e.g. spend most time looking after the child)***

- ○ Yes
- ○ No

What is your <u>highest</u> education qualification?

- ◯ No formal qualifications
- ◯ 1 or more GCSEs/ O levels/ CSEs (any grades), and/or level 1 diploma/ NVQ/ functional skills
- ◯ 5 or more GCSEs (grades A*-C)/ 5+ O levels/ 5+ CSEs (grade 1)/ School Certificate, and/or level 2 diploma/ NVQ/ functional skills
- ◯ A level/ As level, and/or access to higher education diploma, international baccalaureate diploma/ level 3 diploma/ NVQ
- ◯ Certificate of higher education, and/or higher apprenticeship/ HNC/ level 4 diploma/ NVQ
- ◯ Foundation Degree, and/or diploma of higher education/ level 5 diploma/ NVQ
- ◯ First Degree (e.g. BA, BSc) and/or degree apprenticeship/ graduate diploma/ level 6 diploma/ NVQ
- ◯ Master's degree, and/or level 7 diploma/ NVQ/ PGCE/ Postgraduate diploma
- ◯ Doctorate (e.g. PhD or DPhil), and/or level 8 diploma

What is your employment status <u>since the UK COVID-19 lockdown</u> on 23rd March 2020?

- ◯ Working at home (same hours)
- ◯ Working at home (increased hours)
- ◯ Working at home with reduced hours (less than 50% reduction)
- ◯ Working at home with reduced hours (more than 50% reduction)
- ◯ On furlough
- ◯ Self-employed
- ◯ Newly redundant
- ◯ Keyworker
- ◯ Working but not from home and not a key worker
- ◯ Student

◯ Not employed

◯ Other (please state) ____

Home Activities

In the past <u>month</u> how often did you and your child work together on the following? This could be part of learning activities, simply part of your daily routine or through technology. There is no expectation that these activities should be done regularly, especially during these potentially busy and stressful times. We are just interested in what parents are doing, so please answer as honestly as possible.

Counting.

◯ Activity did not occur

◯ Few times a month

◯ About once a week

◯ Few times a week

◯ Almost Daily

Writing out numbers.

◯ Activity did not occur

◯ Few times a month

◯ About once a week

◯ Few times a week

◯ Almost Daily

Scenario-based number games (e.g. 'if I have two toy cars and I take one away, how many cars do I have').

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Counting on fingers/ hands.

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Watching number related or rhyming TV shows (e.g. Number Jacks or Numtums).

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Teaching about measurement (e.g. baking, height).

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Sticker books.

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Sorting shapes.

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Playing with jigsaws.

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Watch educational programmes (e.g. Dora the Explorer).

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Sorting objects by size.

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Comparing sets of objects (e.g. brother has more sweets than mum).

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Pairing/ matching games.

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Playing with building blocks.

- ○ Activity did not occur
- ○ Few times a month
- ○ About once a week
- ○ Few times a week
- ○ Almost Daily

Identifying the names of written numbers.

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Counting out food, dinner plates, knives, forks.

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Creating patterns with objects (e.g. arranging blocks into shapes).

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Counting objects (e.g. ducks in bath, blocks, new toys, books).

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Teaching about money (e.g. informal (playing shop) or formal (buying sweets).

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Time terminology (e.g. big hand, little hand).

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Asking shaped related questions (e.g. 'how many sides does a circle have?').

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Arranging objects by size, shape or colour.

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Singing rhyming songs together (e.g. '1, 2 ,3 4, 5 once I caught a fish alive').

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Reading books together that involve numbers (e.g. hungry caterpillar).

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Timed games (e.g. hide and seek).

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

Everyday activities that involve number (e.g. using money while shopping/ weighing ingredients while cooking).

- ◯ Activity did not occur
- ◯ Few times a month
- ◯ About once a week
- ◯ Few times a week
- ◯ Almost Daily

How many hours per week is your child spending on <u>maths activities</u> at home since covid-19 lockdown?

	0	5	10	15	20	25	30	35	40	45	50
Please drag to select the number of hours ()											

Thinking about how often you engage in home maths activities before COVID-19 lockdown and since COVID-19 lock down, how would you say time spent on home maths activities has changed?

○ We spend much less time on home maths activities

○ We spend a little less time on home maths activities

○ We spend about the same time on home maths activities

○ We spend a little more time on home maths activities

○ We spend much more time on home maths activities

Before UK lock down on 23rd March, who was most responsible for your child's maths learning?

○ Home

○ Nursery/ school

○ Other (please state) ____

How difficult are you finding it to support your child's home maths learning <u>before COVID-19</u>?

○ Not at all difficult

○ Not very difficult

○ Quite difficult

○ Very difficult

How difficult do you find it to support your child's home maths learning <u>since UK lock down on 23rd March</u>?

- ○ Not at all difficult
- ○ Not very difficult
- ○ Quite difficult
- ○ Very difficult

If you have experienced difficulties with learning activities at home, what has been the main barriers for you?

- ☐ Having time
- ☐ Having the resources
- ☐ Having knowledge of the topic
- ☐ Child's attention or concentration
- ☐ Other: please state ____

Maths is a worthwhile and necessary subject.

- ○ Strongly Disagree
- ○ Disagree
- ○ Undecided
- ○ Agree
- ○ Strongly Agree

When I was at school, I enjoyed maths.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

I am confident in my maths abilities.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

A strong maths background helps in adult life.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

It is important for children to develop their maths skills.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

I try to incorporate maths learning into daily life with my child wherever I can.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

Maths skills help with problem-solving in other areas of life.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

I am good at mental calculations.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

Young children learn maths skills best through play.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

Maths skills are useful in all areas of life.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

I find maths activities enjoyable.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

Maths is one of the most important subjects.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

I feel comfortable solving maths problems.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

My career involves/involved maths.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

When I was in school, I was good at maths.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

It is important for children to be exposed to maths concepts everyday.

- ◯ Strongly Disagree
- ◯ Disagree
- ◯ Undecided
- ◯ Agree
- ◯ Strongly Agree

Appendix 2: Supplementary Results

2a) Chapter Four, Study Three

Did children who returned the home mathematical questionnaire differ from children who did not return the home mathematical questionnaire?

To examine whether children who had a questionnaire returned compared to those who did not significantly differed on task performance, an independent samples t-test was conducted. To deal with variables that violated the assumption of normality, confidence intervals with bias corrected accelerated bootstrapped are reported. The results of the t-test for study three are displayed in Table A1.

Table A.1 Task scores for children who had returned a questionnaire compared to those who did not have a returned questionnaire for study one.

	Questionnaire Returned		Questionnaire not returned					
	M	***SD***	***M***	***SD***	**Mean difference**	***t (df)***	***p* value**	**95% CI**
SES (IMD)	3.68	2.94	1.46	1.12	2.22	5.86 (87)	.001	1.58, 2.84
Inhibitory Control	5.23	4.38	3.62	3.74	1.62	2.39 (153)	.014	0.26, 2.88
Working Memory	3.95	1.88	3.17	1.46	0.78	2.90 (152)	.004	0.26, 1.35
Verbal Ability	40.04	13.62	33.12	12.68	6.92	3.28 (155)	.003	2.91, 10.67
Processing Speed	1211.88	264.63	1210.19	287.72	1.69	0.38 (156)	.971	-76.60, 88.19
Counting	15.35	7.84	12.51	6.64	2.84	2.33 (120)	.023	0.48, 5.39
Cardinality	3.93	1.95	3.27	1.48	0.66	2.34 (123)	.019	0.10, 0.17
Mathematical Ability	7.66	5.31	5.08	4.10	2.58	3.32 (123)	.004	1.13, 4.09

Note. M = Mean, *SD* = Standard Deviation, *df* = degrees of freedom, *CI* = Confidence Intervals reported with bias corrected accelerated (BCa) bootstrapping based on 1000 samples, Mathematical Ability refers to the TEMA task.

The t-tests revealed that returned questionnaires were significantly more likely to be from households in higher-SES areas, and children with returned questionnaires also had significantly higher scores on the inhibitory control, working memory, verbal ability, counting, cardinality, and TEMA tasks.

Hierarchical regression predicting mathematical ability from our predictors in Study Three

In Study Three, Chapter Four, we aimed to look at factors which explained the relation between SES and mathematical ability. Therefore, the main analysis reported was a mediation analysis to determine indirect effects. However, a the hierarchical regression analysis is included here to give a summary of the overall findings with all predictors included which correlated with mathematical ability.

To examine which variables predicted early mathematical ability for study three, a three-model hierarchical multiple regression was conducted that included variables that significantly correlated with mathematical ability.

Assumptions for regression analysis were checked. The assumptions of linearity, multicollinearity and homoscedasticity were met, but the assumption of normality of residuals was violated. In order to meet the assumption of normality of residuals, a log10+1 transformation was applied to the dependent variable mathematical ability (TEMA).

Age, sex, and processing speed were included as a covariate for in all models. In Model 1, SES was entered. In Model 2, inhibitory control and working memory were entered. In Model 3, verbal ability was entered. The statistics for the study three are reported in Table A2..

Table A.2 Results of the Hierarchical Regression Analysis Predicting mathematical ability for Study Three.

	Predictor	*b* (95% confidence intervals)	*SE B*	*β*	*p*
Model 1	Constant	-0.52 (-1.20, 0.16)	0.34		.135
	SES (IMD)	0.03 (0.01, 0.05)	0.01	.21	.009
	Sex	0.03 (-0.07, 0.13)	0.05	.05	.550
	Age	0.03 (0.02, 0.05)	0.01	.38	< .001
	Processing Speed	0.00 (0.00, 0.00)	0.00	-.15	.068
Model 2	Constant	-0.22 (-0.87, 0.43)	0.33		.503
	SES (IMD)	0.02 (0.00, 0.044)	0.01	.13	.082
	Sex	0.01 (-0.08, 0.11)	0.05	.02	.810
	Age	0.02 (0.01, 0.03)	0.01	.24	.003
	Processing Speed	0.00 (0.00, 0.00)	0.00	-.15	.048
	Working Memory	0.05 (0.02, 0.08)	0.02	.26	.001
	Inhibitory Control	0.02 (0.01, 0.03)	0.01	.21	.008
Model 3	Constant	-0.42 (-1.05, 0.20)	0.32		.183
	SES (IMD)	0.01 (-0.01, 0.03)	0.01	.06	.454
	Sex	0.01 (-0.08, 0.10)	0.05	.02	.832
	Age	0.02 (0.01, 0.03)	0.01	.23	.002
	Processing Speed	0.00 (0.00, 0.00)	0.00	-.12	.109
	Working Memory	0.04 (0.01, 0.06)	0.01	.19	.014
	Inhibitory Control	0.01 (0.00, 0.02)	0.01	.10	.188
	Verbal Ability	0.01 (0.00, 0.01)	0.00	.33	< .001

Note. Mathematical ability (TEMA) scores were transformed using log10. R^2 = .25 for Model 1, ΔR^2 = .32 for Model 2, ΔR^2 = .40 for Model 3. Pairwise deletion was used for missing data.

For study three, in Model 1, SES and age were significant predictors of mathematical ability, accounting for 25% of variance ($F_{(4,129)} = 10.56$, $p < .001$). Sex and processing speed did not significantly predict mathematical ability. In Model 2, working memory, inhibitory control and processing speed were significant predictors of mathematical ability, overall accounting for 32% of variance in mathematical ability ($F_{(6,127)} = 11.55$, $p < .001$). After introducing these variables in Model 2, SES was no longer a significant predictor, and sex continued to not significantly predict mathematical ability. This suggests that working memory and inhibitory control may be accounting for the socioeconomic gradient in mathematical ability. In Model 3, verbal ability was a significant predictor of mathematical ability. Working memory remained a significant predictor, but inhibitory control and processing speed were no longer significant predictors of mathematical ability. The final model accounted for 40% of variance ($F_{(7,126)} = 13.39$, $p < .001$).

2b) Chapter Four, Study Four

Did children who returned the home mathematical questionnaire differ from children who did not return the home mathematical questionnaire?

To examine whether children who had a questionnaire returned compared to those who did not significantly differed on task performance, an independent samples t-test was conducted. To deal with variables that violated the assumption of normality, confidence intervals with bias corrected accelerated bootstrapped are reported. The results of the t-test for study four are displayed in Table A3.

Table A.3 Task scores for children who had returned a questionnaire compared to those who did not have a returned questionnaire for study four.

	Questionnaire Returned		**Questionnaire not returned**		**Mean difference**	***t (df)***	***p* value**	**95% CI**
	M	***SD***	***M***	***SD***				
Inhibitory Control	6.09	4.05	5.10	4.49	0.99	1.27 (143)	.214	-0.90, 2.81
Working Memory	3.05	2.04	2.51	1.86	0.53	1.43 (143)	.138	-0.18, 1.19
Verbal Ability	38.55	13.83	36.05	11.71	2.50	1.00 (142)	.293	-2.23, 7.05
Processing Speed	1403.57	362.85	1485.63	368.71	-82.07	1.19 (140)	.204	-227.64, 62.71
Mathematical Ability	7.12	6.30	5.67	5.14	1.45	1.28 (141)	.166	-0.61, 3.43

Note. *M* = Mean, *SD* = Standard Deviation, *df* = degrees of freedom, *CI* = Confidence Intervals reported with bias corrected accelerated (BCa) bootstrapping based on 1000 samples.

The t-tests revealed no differences on the experimental tasks between preschoolers whose parents completed the questionnaire to those who did not. It was not possible to assess SES differences in questionnaire return, as we only had SES information for children who returned the questionnaire.

Hierarchical regression predicting mathematical ability from our predictors in Study Four

In Study Four, Chapter Four, we aimed to look at factors which explained the relation between SES and mathematical ability. Therefore, the main analysis reported was a mediation analysis to determine indirect effects. However, the hierarchical regression analysis is included here to give a summary of the overall findings with all predictors included which correlated with mathematical ability.

To examine which variables predicted early mathematical ability for study four, a three-model hierarchical multiple regression was conducted that included variables that significantly correlated with mathematical ability. Assumptions for regression analysis were checked and all assumptions were met.

Age, sex, and processing speed were included as a covariate for in all models. In Model 1, SES was entered. In Model 2, inhibitory control and working memory were entered. In Model 3, verbal ability was entered. The statistics for the analysis are reported in Table A4.

Table A.4 Results of the Hierarchical Regression Analyses Predicting Mathematical Ability for Study Four.

	Predictor	***b* (95% confidence intervals)**	***SE B***	***β***	***p***
Model 1	Constant	-10.04 (-23.94, 3.87)	7.01		.155
	SES (Mother's Education)	0.79 (0.33, 1.25)	0.23	.32	.001
	Sex	1.68 (-0.47, 3.83)	1.08	.14	.124
	Age	0.39 (0.12, 0.65)	0.13	.26	.005
	Processing Speed	0.00 (-0.01, 0.00)	0.00	-.19	.039
Model 2	Constant	-8.06 (-19.58, 3.47)	5.81		.168
	SES	0.37 (-0.04, 0.77)	0.20	.15	.075
	Sex	0.78 (-1.02, 2.58)	0.91	.07	.391
	Age	0.22 (-0.01, 0.44)	0.11	.15	.056
	Processing Speed	0.00 (-0.01, 0.00)	0.00	-.13	.089
	Working Memory	1.10 (0.64, 1.56)	0.23	.37	< .001
	Inhibitory Control	0.51 (0.29, 0.74)	0.11	.36	< .001
Model 3	Constant	-9.14 (-20.15, 1.87)	5.55		.102
	SES	0.15 (-0.26, 0.56)	0.21	.06	.462
	Sex	0.55 (-1.17, 2.27)	0.87	.05	.527
	Age	0.16 (-0.06, 0.37)	0.11	.11	.157
	Processing Speed	0.00 (0.00, 0.00)	0.00	-.09	.225
	Working Memory	0.92 (0.48, 1.37)	0.23	.31	< .001
	Inhibitory Control	0.45 (0.23, 0.67)	0.11	.31	< .001
	Verbal Ability	0.13 (0.05, 0.20)	0.04	.28	.002

Note. R^2 = .22 for Model 1, Δ R^2 = .46 for Model 2, Δ R^2 = .49 for Model 3. Pairwise deletion was used for missing data.

For Study Four, in Model 1, SES, age, and processing speed were significant predictors of mathematical ability, accounting for 22% of variance (F(4,98) = 7.01, p < .001). Sex was not a significant predictor of mathematical ability. In Model 2, working memory and inhibitory control were significant predictors of mathematical ability, overall accounting for 48% of variance in mathematical ability ($F(6,96) = 14.68.93$, $p < .001$). After introducing these variables in Model 2, mother's education and age was no longer significant predictors of mathematical ability, suggesting (as with study one) that working memory and inhibitory control may be accounting for the socioeconomic gradient in mathematical ability. In Model 3, verbal ability was added, which was a significant predictor of mathematical ability. The final model accounted for 53% of variance ($F(7,95) = 15.35$, $p < .001$).

Appendix 3: Summary of Meta-analytic Sample in Chapter Five

Table A.5 Summary of Studies and effect sizes in the Meta-Analysis.

Paper ID	Study ID	Authors	Year	Source	Sample Size	*r*	Child Age in Months	Study Design	Country of Data Collection	Geographical Location of Data Collection	Type of Mathematical Ability Measure
1	1	Blevins-Knabe et al.	2000	Published Literature	64	.14	53	Concurrent	United States	North America	Composite
2	2	Cheung et al.	2018	Published Literature	673	.09	51	Concurrent	Philippines	-	Number Knowledge
2	2	Cheung et al.	2018	Published Literature	673	.06	51	Concurrent	Philippines	-	Number Knowledge
2	2	Cheung et al.	2018	Published Literature	673	.05	51	Concurrent	Philippines	-	Counting
2	2	Cheung et al.	2018	Published Literature	673	.10	51	Concurrent	Philippines	-	Number Knowledge
2	2	Cheung et al.	2018	Published Literature	673	.09	51	Concurrent	Philippines	-	Magnitude Estimation
2	2	Cheung et al.	2018	Published Literature	673	.09	51	Concurrent	Philippines	-	Operations
3	3	Ciping et al.	2015	Published Literature	177	-.18	80	Longitudinal	China	-	Composite
3	3	Ciping et al.	2015	Published Literature	177	.08	80	Longitudinal	China	-	Composite
3	3	Ciping et al.	2015	Published Literature	177	-.02	90	Longitudinal	China	-	Composite
3	3	Ciping et al.	2015	Published Literature	177	.12	90	Longitudinal	China	-	Composite
3	3	Ciping et al.	2015	Published Literature	177	-.11	90	Longitudinal	China	-	Composite
3	3	Ciping et al.	2015	Published Literature	177	.05	90	Longitudinal	China	-	Composite

4	4	Dearing et al.	2012	Published Literature	127	.29	81	Concurrent	United States	North America	Operations
4	4	Dearing et al.	2012	Published Literature	127	-.11	81	Concurrent	United States	North America	Spatial Skills
5	5	DeFlorio & Beliakoff	2015	Published Literature	178	.17	47	Concurrent	United States	North America	Composite
6	6	Del Río et al.	2017	Published Literature	178	.21	67	Concurrent	Chile	-	Composite
6	6	Del Rio et al.	2017	Published Literature	178	-.05	67	Concurrent	Chile	-	Composite
7	7	Huang et al.	2017	Published Literature	103	.20	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	103	.28	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	103	.08	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	103	.37	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	103	.15	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	103	.18	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	103	.00	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	103	.14	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	104	.20	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	104	.22	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	104	.15	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	104	.38	60	Concurrent	Hong Kong	-	Operations

7	7	Huang et al.	2017	Published Literature	104	.16	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	104	.09	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	104	.03	60	Concurrent	Hong Kong	-	Operations
7	7	Huang et al.	2017	Published Literature	104	.26	60	Concurrent	Hong Kong	-	Operations
8	8	Huntsinger et al.	2016	Published Literature	200	.00	60	Longitudinal	United States	North America	Composite
8	8	Huntsinger et al.	2016	Published Literature	200	.40	60	Longitudinal	United States	North America	Composite
8	8	Huntsinger et al.	2016	Published Literature	200	.17	60	Longitudinal	United States	North America	Composite
8	8	Huntsinger et al.	2016	Published Literature	97	.09	71	Longitudinal	United States	North America	Composite
8	8	Huntsinger et al.	2016	Published Literature	97	.50	71	Longitudinal	United States	North America	Composite
8	8	Huntsinger et al.	2016	Published Literature	97	.13	71	Longitudinal	United States	North America	Composite
8	8	Huntsinger et al.	2016	Published Literature	97	.21	71	Longitudinal	United States	North America	Composite
8	8	Huntsinger et al.	2016	Published Literature	97	-.14	71	Longitudinal	United States	North America	Composite
8	8	Huntsinger et al.	2016	Published Literature	97	.27	71	Longitudinal	United States	North America	Composite
9	9	Kleemans et al.	2012	Published Literature	89	.47	73	Concurrent	Netherlands	Europe (exclude UK)	Composite
10	10	LeFevre et al.	2010	Published Literature	104	.37	70	Concurrent	Canada	North America	Composite
10	10	LeFevre et al.	2010	Published Literature	104	.05	70	Concurrent	Canada	North America	Composite
10	10	LeFevre et al.	2010	Published Literature	104	.06	70	Concurrent	Canada	North America	Composite
10	10.1	LeFevre et al.	2010	Published Literature	100	.38	70	Concurrent	Greece	Europe (exclude UK)	Composite

10	10.1	LeFevre et al.	2010	Published Literature	100	.02	70	Concurrent	Greece	Europe (exclude UK)	Composite
10	10.1	LeFevre et al.	2010	Published Literature	100	.03	70	Concurrent	Greece	Europe (exclude UK)	Composite
11	11	Lefevre et al.	2009	Published Literature	146	-.06	82	Concurrent	Canada	North America	Composite
11	11	LeFevre et al.	2009	Published Literature	146	-.14	82	Concurrent	Canada	North America	Composite
11	11	LeFevre et al.	2009	Published Literature	146	.27	82	Concurrent	Canada	North America	Composite
11	11	LeFevre et al.	2009	Published Literature	146	.02	82	Concurrent	Canada	North America	Composite
11	11	LeFevre et al.	2009	Published Literature	146	.07	82	Concurrent	Canada	North America	Operations
11	11	LeFevre et al.	2009	Published Literature	146	-.19	82	Concurrent	Canada	North America	Operations
11	11	LeFevre et al.	2009	Published Literature	146	.26	82	Concurrent	Canada	North America	Operations
11	11	LeFevre et al.	2009	Published Literature	146	.16	82	Concurrent	Canada	North America	Operations
12	12	Liu et al.	2019	Published Literature	109	.08	38	Concurrent	Hong Kong	-	Composite
12	12	Liu et al.	2019	Published Literature	109	-.04	38	Concurrent	Hong Kong	-	Composite
12	12	Liu et al.	2019	Published Literature	109	-.12	38	Concurrent	Hong Kong	-	Composite
12	12	Liu et al.	2019	Published Literature	109	.02	38	Concurrent	Hong Kong	-	Composite
12	12	Liu et al.	2019	Published Literature	109	.10	38	Concurrent	Hong Kong	-	Composite
12	12	Liu et al.	2019	Published Literature	109	.06	38	Concurrent	Hong Kong	-	Composite
12	12	Liu et al.	2019	Published Literature	109	.07	38	Concurrent	Hong Kong	-	Composite
12	12	Liu et al.	2019	Published Literature	109	.21	38	Concurrent	Hong Kong	-	Composite

13	13	Manolitsis et al.	2013	Published Literature	82	.09	65	Longitudinal	Greece	Europe (exclude UK)	Composite
13	13	Manolitsis et al.	2013	Published Literature	82	.28	65	Longitudinal	Greece	Europe (exclude UK)	Counting
13	13	Manolitsis et al.	2013	Published Literature	82	.14	72	Longitudinal	Greece	Europe (exclude UK)	Composite
13	13	Manolitsis et al.	2013	Published Literature	82	.01	72	Longitudinal	Greece	Europe (exclude UK)	Counting
13	13	Manolitsis et al.	2013	Published Literature	82	-.02	84	Longitudinal	Greece	Europe (exclude UK)	Composite
14	14	Missall et al.	2015	Published Literature	72	.13	54	Concurrent	United States	North America	Number Knowledge
14	14	Missall et al.	2015	Published Literature	72	-.03	54	Concurrent	United States	North America	Counting
14	14	Missall et al.	2015	Published Literature	72	.21	54	Concurrent	United States	North America	Number Knowledge
14	14	Missall et al.	2015	Published Literature	72	-.13	54	Concurrent	United States	North America	Number Knowledge
14	14	Missall et al.	2015	Published Literature	72	-.06	54	Concurrent	United States	North America	Composite
14	14	Missall et al.	2015	Published Literature	72	.21	54	Concurrent	United States	North America	Composite
15	15	Mutaf Yıldız et al.	2018	Published Literature	44	.31	68	Concurrent	Belgium	Europe (exclude UK)	Composite
15	15	Mutaf Yildiz et al.	2018	Published Literature	44	.17	68	Concurrent	Belgium	Europe (exclude UK)	Composite
15	15	Mutaf Yildiz et al.	2018	Published Literature	44	-.03	68	Concurrent	Belgium	Europe (exclude UK)	Composite
15	15	Mutaf Yildiz et al.	2018	Published Literature	44	.16	68	Concurrent	Belgium	Europe (exclude UK)	Composite
16	16	Napoli & Purpura	2018	Published Literature	114	.29	49	Longitudinal	United States	North America	Composite

16	16	Napoli & Purpura	2018	Published Literature	114	.40	58	Longitudinal	United States	North America	Composite
17	17	Niklas & Schneider	2014	Published Literature	493	.09	73	Longitudinal	Germany	Europe (exclude UK)	Composite
17	17	Niklas & Schneider	2014	Published Literature	340	.12	78	Longitudinal	Germany	Europe (exclude UK)	Composite
17	17	Niklas & Schneider	2014	Published Literature	340	.15	86	Longitudinal	Germany	Europe (exclude UK)	Composite
18	18	Niklas et al.	2016	Published Literature	113	.47	53	Concurrent	Australia	-	Composite
18	18	Niklas et al.	2016	Published Literature	113	.19	53	Concurrent	Australia	-	Composite
19	19	Niklas et al.	2016	Published Literature	1686	.05	48	Longitudinal	Australia	-	Composite
19	19	Niklas et al.	2016	Published Literature	1686	.03	60	Longitudinal	Australia	-	Composite
19	19	Niklas et al.	2016	Published Literature	1686	.06	84	Longitudinal	Australia	-	Composite
20	20	Ramani et al.	2015	Published Literature	26	.55	52	Concurrent	United States	North America	Composite
20	20	Ramani et al.	2015	Published Literature	26	.46	52	Concurrent	United States	North America	Composite
20	20	Ramani et al.	2015	Published Literature	26	-.07	52	Concurrent	United States	North America	Composite
20	20	Ramani et al.	2015	Published Literature	26	.20	52	Concurrent	United States	North America	Composite
20	20	Ramani et al.	2015	Published Literature	26	.35	52	Concurrent	United States	North America	Composite
20	20	Ramani et al.	2015	Published Literature	26	.24	52	Concurrent	United States	North America	Composite
21	21	Segers et al.	2015	Published Literature	60	.41	69	Concurrent	Netherlands	Europe (exclude UK)	Composite
22	22	Skwarchuk	2009	Published Literature	25	.52	58	Concurrent	Canada	North America	Composite

23	23	Skwarchuk et al.	2014	Published Literature	121	-.03	70	Longitudinal	Canada	North America	Non-Symbolic
23	23	Skwarchuk et al.	2014	Published Literature	121	-.08	70	Longitudinal	Canada	North America	Composite
23	23	Skwarchuk et al.	2014	Published Literature	121	.14	70	Longitudinal	Canada	North America	Non-Symbolic
23	23	Skwarchuk et al.	2014	Published Literature	121	.27	70	Longitudinal	Canada	North America	Composite
24	24	Soto-Calvo et al.	2019	Published Literature	274	.17	48	Concurrent	United Kingdom	United Kingdom	Counting
24	24	Soto-Calvo et al.	2019	Published Literature	274	.24	48	Concurrent	United Kingdom	United Kingdom	Number Knowledge
24	24	Soto-Calvo et al.	2019	Published Literature	274	.23	48	Concurrent	United Kingdom	United Kingdom	Number Knowledge
24	24	Soto-Calvo et al.	2019	Published Literature	274	.29	48	Concurrent	United Kingdom	United Kingdom	Number Knowledge
24	24	Soto-Calvo et al.	2019	Published Literature	274	.26	48	Concurrent	United Kingdom	United Kingdom	Number Knowledge
24	24	Soto-Calvo et al.	2019	Published Literature	274	.17	48	Concurrent	United Kingdom	United Kingdom	Operations
24	24	Soto-Calvo et al.	2019	Published Literature	274	.17	48	Concurrent	United Kingdom	United Kingdom	Operations
25	25.1	Susprregu y et al.	2018	Published Literature	390	.17	55	Longitudinal	Chile	-	Composite
25	25.1	Susperreg uy et al.	2018	Published Literature	390	-.06	63	Longitudinal	Chile	-	Magnitude Estimation
25	25.1	Susperreg uy et al.	2018	Published Literature	390	-.04	63	Longitudinal	Chile	-	Non-Symbolic
25	25.1	Susperreg uy et al.	2018	Published Literature	390	-.12	63	Longitudinal	Chile	-	Composite
25	25.1	Susperreg uy et al.	2018	Published Literature	390	-.01	63	Longitudinal	Chile	-	Magnitude Estimation
25	25.1	Susperreg uy et al.	2018	Published Literature	390	-.04	63	Longitudinal	Chile	-	Non-Symbolic
25	25.1	Susperreg uy et al.	2018	Published Literature	390	.15	55	Longitudinal	Chile	-	Composite

25	25.1	Susperreguy et al.	2018	Published Literature	390	.12	63	Longitudinal	Chile	-	Magnitude Estimation
25	25.1	Susperreguy et al.	2018	Published Literature	390	.11	63	Longitudinal	Chile	-	Non-Symbolic
25	25.1	Susperreguy et al.	2018	Published Literature	390	.25	63	Longitudinal	Chile	-	Composite
25	25.1	Susperreguy et al.	2018	Published Literature	390	-.17	63	Longitudinal	Chile	-	Magnitude Estimation
25	25.1	Susperreguy et al.	2018	Published Literature	390	.08	63	Longitudinal	Chile	-	Non-Symbolic
26	26	Thompson et al.	2017	Published Literature	71	.17	42	Concurrent	United States	North America	Composite
26	26	Thompson et al.	2017	Published Literature	71	-.05	42	Concurrent	United States	North America	Composite
26	26	Thompson et al.	2017	Published Literature	113	.23	53	Concurrent	United States	North America	Composite
26	26	Thompson et al.	2017	Published Literature	113	-.10	53	Concurrent	United States	North America	Composite
27	27	Vandermaas-Peeler & Pittard	2014	Published Literature	18	.57	61	Concurrent	United States	North America	Composite
28	28	Vasilyeva et al.	2018	Published Literature	98	.41	82	Concurrent	Russia	-	Number Knowledge
28	28	Vasilyeva et al.	2018	Published Literature	98	.13	82	Concurrent	Russia	-	Magnitude Estimation
28	28	Vasilyeva et al.	2018	Published Literature	98	.34	82	Concurrent	Russia	-	Operations
28	28	Vasilyeva et al.	2018	Published Literature	98	.18	82	Concurrent	Russia	-	Number Knowledge
28	28	Vasilyeva et al.	2018	Published Literature	98	.50	82	Concurrent	Russia	-	Magnitude Estimation
28	28	Vasilyeva et al.	2018	Published Literature	98	.40	82	Concurrent	Russia	-	Operations
29	29	Zambrzycka et al.	2017	Published Literature	33	.36	27	Concurrent	Canada	North America	Number Knowledge

29	29	Zambrzcka et al.	2017	Published Literature	33	.30	27	Concurrent	Canada	North America	Number Knowledge
30	30	Zippert & Ramani	2017	Published Literature	43	.25	53	Concurrent	United States	North America	Composite
30	30	Zippert & Ramani	2017	Published Literature	43	.12	53	Concurrent	United States	North America	Composite
30	30	Zippert & Ramani	2017	Published Literature	43	-.10	53	Concurrent	United States	North America	Composite
30	30	Zippert & Ramani	2017	Published Literature	43	.22	53	Concurrent	United States	North America	Composite
30	30	Zippert & Ramani	2017	Published Literature	43	.41	53	Concurrent	United States	North America	Composite
30	30	Zippert & Ramani	2017	Published Literature	43	.10	53	Concurrent	United States	North America	Composite
31	31	Bernabini et al.	2020	Published Literature	64	.40	69	Concurrent	Italy	Europe (exclude UK)	Composite
32	32	Cahoon et al.	2021	Published Literature	128	.01	48	Longitudinal	United Kingdom	United Kingdom	Composite
32	32	Cahoon et al.	2021	Published Literature	128	-.11	48	Longitudinal	United Kingdom	United Kingdom	Number Knowledge
32	32	Cahoon et al.	2021	Published Literature	128	-.09	48	Longitudinal	United Kingdom	United Kingdom	Number Knowledge
32	32	Cahoon et al.	2021	Published Literature	128	-.05	48	Longitudinal	United Kingdom	United Kingdom	Magnitude Estimation
32	32	Cahoon et al.	2021	Published Literature	128	-.01	48	Longitudinal	United Kingdom	United Kingdom	Non-Symbolic + Magnitude Estimation
32	32	Cahoon et al.	2021	Published Literature	118	-.16	56	Longitudinal	United Kingdom	United Kingdom	Composite
32	32	Cahoon et al.	2021	Published Literature	118	.02	56	Longitudinal	United Kingdom	United Kingdom	Number Knowledge
32	32	Cahoon et al.	2021	Published Literature	118	-.05	56	Longitudinal	United Kingdom	United Kingdom	Number Knowledge
32	32	Cahoon et al.	2021	Published Literature	118	-.04	56	Longitudinal	United Kingdom	United Kingdom	Magnitude Estimation

32	32	Cahoon et al.	2021	Published Literature	118	-.08	56	Longitudinal	United Kingdom	United Kingdom	Non-Symbolic + Magnitude Estimation
32	32	Cahoon et al.	2021	Theses	93	-.08	NA	Longitudinal	United Kingdom	United Kingdom	Composite
33	33	Cheung et al.	2020	Published Literature	290	.07	80	Concurrent	Philippines	-	Number Knowledge
33	33	Cheung et al.	2020	Published Literature	290	.10	80	Concurrent	Philippines	-	Number Knowledge
33	33	Cheung et al.	2020	Published Literature	290	.09	80	Concurrent	Philippines	-	Counting
33	33	Cheung et al.	2020	Published Literature	290	.18	80	Concurrent	Philippines	-	Number Knowledge
33	33	Cheung et al.	2020	Published Literature	290	.08	80	Concurrent	Philippines	-	Magnitude Estimation
34	34	De Keyser et al.	2020	Published Literature	353	.02	70	Concurrent	Belgium	Europe (exclude UK)	Composite
34	34	De Keyser et al	2020	Published Literature	353	-.09	70	Concurrent	Belgium	Europe (exclude UK)	Spatial Skills
35	35	Elliott	2020	Published Literature	3111	.11	36	Longitudinal	United States	North America	Composite
35	35	Elliott	2020	Published Literature	3111	.10	36	Longitudinal	United States	North America	Composite
35	35	Elliott	2020	Published Literature	3111	.09	36	Longitudinal	United States	North America	Counting
35	35	Elliott	2020	Published Literature	3111	.07	43	Longitudinal	United States	North America	Composite
35	35	Elliott	2020	Published Literature	3111	.08	43	Longitudinal	United States	North America	Composite
35	35	Elliott	2020	Published Literature	3111	.04	43	Longitudinal	United States	North America	Counting
35	35	Elliott	2020	Published Literature	3111	.05	43	Longitudinal	United States	North America	Composite
35	35	Elliott	2020	Published Literature	3111	.06	43	Longitudinal	United States	North America	Composite

35	35	Elliott	2020	Published Literature	3111	.06	43	Longitudinal	United States	North America	Counting
36	36	Keating et al.	2021	Published Literature	72	.12	68	Concurrent	United States	North America	Composite
37	37	Khanolainen et al.	2020	Published Literature	2525	.00	78	Longitudinal	Finland	Europe (exclude UK)	Operations
37	37	Khanolainen et al.	2020	Published Literature	2525	.05	78	Longitudinal	Finland	Europe (exclude UK)	Operations
37	37	Khanolainen et al.	2020	Published Literature	2525	.02	90	Longitudinal	Finland	Europe (exclude UK)	Operations
37	37	Khanolainen et al.	2020	Published Literature	2525	.04	90	Longitudinal	Finland	Europe (exclude UK)	Operations
38	38	King & Purpura	2021	Published Literature	125	.22	50	Longitudinal	United States	North America	Composite
38	38	King & Purpura	2021	Published Literature	125	.34	54	Longitudinal	United States	North America	Composite
38	38	King & Purpura	2021	Published Literature	125	.19	50	Longitudinal	United States	North America	Composite
38	38	King & Purpura	2021	Published Literature	125	.31	54	Longitudinal	United States	North America	Composite
39	39	King et al.	2021	Published Literature	37	.13	56	Concurrent	United States	North America	Composite
39	39	King et al.	2021	Published Literature	61	.13	54	Concurrent	United States	North America	Composite
40	40.1	Lê & Noël	2020	Published Literature	104	.41	55	Concurrent	Vietnam & Belgium	-	Counting
40	40.1	Lê & Noël	2020	Published Literature	104	.30	55	Concurrent	Vietnam & Belgium	-	Number Knowledge
40	40.1	Lê & Noël	2020	Published Literature	104	.24	55	Concurrent	Vietnam & Belgium	-	Number Knowledge
40	40.1	Lê & Noël	2020	Published Literature	104	.29	55	Concurrent	Vietnam & Belgium	-	Number Knowledge
40	40.1	Lê & Noël	2020	Published Literature	104	.33	55	Concurrent	Vietnam & Belgium	-	Number Knowledge
40	40.1	Lê & Noël	2020	Published Literature	104	.17	55	Concurrent	Vietnam & Belgium	-	Number Knowledge

40	40.1	Lê & Noël	2020	Published Literature	104	.25	55	Concurrent	Vietnam & Belgium	-	Operations
40	40.1	Lê & Noël	2020	Published Literature	104	.10	55	Concurrent	Vietnam & Belgium	-	Non-Symbolic
40	40.2	Lê & Noël	2020	Published Literature	104	.26	55	Concurrent	Vietnam & Belgium	-	Counting
40	40.2	Lê & Noël	2020	Published Literature	104	.26	55	Concurrent	Vietnam & Belgium	-	Number Knowledge
40	40.2	Lê & Noël	2020	Published Literature	104	.17	55	Concurrent	Vietnam & Belgium	-	Number Knowledge
40	40.2	Lê & Noël	2020	Published Literature	104	.21	55	Concurrent	Vietnam & Belgium	-	Number Knowledge
40	40.2	Lê & Noël	2020	Published Literature	104	.26	55	Concurrent	Vietnam & Belgium	-	Number Knowledge
40	40.2	Lê & Noël	2020	Published Literature	104	.14	55	Concurrent	Vietnam & Belgium	-	Number Knowledge
40	40.2	Lê & Noël	2020	Published Literature	104	.27	55	Concurrent	Vietnam & Belgium	-	Operations
40	40.2	Lê & Noël	2020	Published Literature	104	.19	55	Concurrent	Vietnam & Belgium	-	Non-Symbolic
41	41	Lehrl et al.	2019	Published Literature	554	.01	60	Longitudinal	Germany	Europe (exclude UK)	Composite
42	42	Marinova et al.,	2021	Published Literature	193	.06	47	Concurrent	Belgium	Europe (exclude UK)	Number Knowledge
42	42	Marinova et al.	2021	Published Literature	193	.32	47	Concurrent	Belgium	Europe (exclude UK)	Number Knowledge
42	42	Marinova et al.	2021	Published Literature	193	.06	47	Concurrent	Belgium	Europe (exclude UK)	Number Knowledge
42	42	Marinova et al.	2021	Published Literature	193	.20	47	Concurrent	Belgium	Europe (exclude UK)	Number Knowledge
42	42	Marinova et al.	2021	Published Literature	193	.01	47	Concurrent	Belgium	Europe (exclude UK)	Number Knowledge
42	42	Marinova et al.	2021	Published Literature	193	.32	47	Concurrent	Belgium	Europe (exclude UK)	Number Knowledge
43	43	McCormick et al.	2020	Published Literature	307	-.11	56	Longitudinal	United States	North America	Composite

43	43	McCormick et al.	2020	Published Literature	307	.04	56	Longitudinal	United States	North America	Composite
43	43	McCormick et al.	2020	Published Literature	307	-.09	62	Longitudinal	United States	North America	Composite
43	43	McCormick et al.	2020	Published Literature	307	.00	62	Longitudinal	United States	North America	Composite
44	44	Oğul & Arnas	2020	Published Literature	40	.38	56	Concurrent	Turkey	-	Composite
45	45	Pardo et al.	2020	Published Literature	212	-.02	70	Concurrent	Spain	Europe (exclude UK)	Magnitude Estimation
45	45	Pardo et al.	2020	Published Literature	212	-.10	70	Concurrent	Spain	Europe (exclude UK)	Non-Symbolic
45	45	Pardo et al.	2020	Published Literature	212	-.14	70	Concurrent	Spain	Europe (exclude UK)	Number Knowledge
45	45	Pardo et al.	2020	Published Literature	212	.41	70	Concurrent	Spain	Europe (exclude UK)	Magnitude Estimation
45	45	Pardo et al.	2020	Published Literature	212	.17	70	Concurrent	Spain	Europe (exclude UK)	Non-Symbolic
45	45	Pardo et al.	2020	Published Literature	212	.12	70	Concurrent	Spain	Europe (exclude UK)	Number Knowledge
46	46	Purpura et al.	2020	Published Literature	129	-.20	57	Concurrent	United States	North America	Composite
46	46	Purpura et al.	2020	Published Literature	129	.01	57	Concurrent	United States	North America	Spatial Skills
47	47	Silinskas et al.	2020	Published Literature	229	.09	81	Concurrent	Lithuania	Europe (exclude UK)	Operations
47	47	Silinskas et al.	2020	Published Literature	337	.03	88	Concurrent	Lithuania	Europe (exclude UK)	Operations
47	47	Silinskas et al.	2020	Published Literature	341	.02	93	Concurrent	Lithuania	Europe (exclude UK)	Operations
47	47	Silinskas et al.	2020	Published Literature	337	-.21	88	Concurrent	Lithuania	Europe (exclude UK)	Operations
47	47	Silinskas et al.	2020	Published Literature	341	-.23	93	Concurrent	Lithuania	Europe (exclude UK)	Operations
47	47	Silinskas et al.	2020	Published Literature	341	-.26	93	Concurrent	Lithuania	Europe (exclude UK)	Operations

48	48	Silver et al.	2020	Published Literature	112	.19	49	Concurrent	United States	North America	Composite
48	48	Silver et al.	2020	Published Literature	112	.05	49	Concurrent	United States	North America	Non-Symbolic
49	49	Silver et al.	2021	Published Literature	114	.18	47	Longitudinal	United States	North America	Composite
49	49	Silver et al.	2021	Published Literature	114	.21	47	Longitudinal	United States	North America	Composite
50	50	Soto-Calvo et al.	2020	Published Literature	274	.18	48	Concurrent	United Kingdom	United Kingdom	Counting
50	50	Soto-Calvo et al.	2020	Published Literature	274	.25	48	Concurrent	United Kingdom	United Kingdom	Number Knowledge
50	50	Soto-Calvo et al.	2020	Published Literature	274	.24	48	Concurrent	United Kingdom	United Kingdom	Number Knowledge
50	50	Soto-Calvo et al.	2020	Published Literature	274	.29	48	Concurrent	United Kingdom	United Kingdom	Number Knowledge
50	50	Soto-Calvo et al.	2020	Published Literature	274	.27	48	Concurrent	United Kingdom	United Kingdom	Number Knowledge
50	50	Soto-Calvo et al.	2020	Published Literature	274	.18	48	Concurrent	United Kingdom	United Kingdom	Operations
50	50	Soto-Calvo et al.	2020	Published Literature	274	.18	48	Concurrent	United Kingdom	United Kingdom	Operations
50	50	Soto-Calvo et al.	2020	Published Literature	232	.18	63	Concurrent	United Kingdom	United Kingdom	Counting
50	50	Soto-Calvo et al.	2020	Published Literature	232	.24	63	Concurrent	United Kingdom	United Kingdom	Number Knowledge
50	50	Soto-Calvo et al.	2020	Published Literature	232	.23	63	Concurrent	United Kingdom	United Kingdom	Number Knowledge
50	50	Soto-Calvo et al.	2020	Published Literature	232	.25	63	Concurrent	United Kingdom	United Kingdom	Number Knowledge
50	50	Soto-Calvo et al.	2020	Published Literature	232	.28	63	Concurrent	United Kingdom	United Kingdom	Number Knowledge
50	50	Soto-Calvo et al.	2020	Published Literature	232	.18	63	Concurrent	United Kingdom	United Kingdom	Operations
50	50	Soto-Calvo et al.	2020	Published Literature	232	.11	63	Concurrent	United Kingdom	United Kingdom	Operations

50	50	Soto-Calvo et al.	2020	Published Literature	232	.19	63	Concurrent	United Kingdom	United Kingdom	Composite
51	51	Susperreguy, et al.	2020	Published Literature	419	.01	55	Longitudinal	Chile	-	Composite
51	51	Susperreguy et al.	2020	Published Literature	419	.15	55	Longitudinal	Chile	-	Composite
51	51	Susperreguy et al.	2020	Published Literature	406	-.06	63	Longitudinal	Chile	-	Magnitude Estimation
51	51	Susperreguy et al.	2020	Published Literature	406	.12	63	Longitudinal	Chile	-	Magnitude Estimation
51	51	Susperreguy et al.	2020	Published Literature	406	-.04	63	Longitudinal	Chile	-	Non-Symbolic
51	51	Susperreguy et al.	2020	Published Literature	406	.11	63	Longitudinal	Chile	-	Non-Symbolic
51	51	Susperreguy et al.	2020	Published Literature	406	-.12	63	Longitudinal	Chile	-	Composite
51	51	Susperreguy et al.	2020	Published Literature	406	.25	63	Longitudinal	Chile	-	Composite
51	51	Susperreguy et al.	2020	Published Literature	406	-.01	63	Longitudinal	Chile	-	Magnitude Estimation
51	51	Susperreguy et al.	2020	Published Literature	406	-.17	63	Longitudinal	Chile	-	Magnitude Estimation
51	51	Susperreguy et al.	2020	Published Literature	368	.01	70	Longitudinal	Chile	-	Magnitude Estimation
51	51	Susperreguy et al.	2020	Published Literature	368	.02	70	Longitudinal	Chile	-	Magnitude Estimation
51	51	Susperreguy et al.	2020	Published Literature	368	.00	70	Longitudinal	Chile	-	Non-Symbolic
51	51	Susperreguy et al.	2020	Published Literature	368	.20	70	Longitudinal	Chile	-	Non-Symbolic
51	51	Susperreguy et al.	2020	Published Literature	368	-.03	70	Longitudinal	Chile	-	Composite
51	51	Susperreguy et al.	2020	Published Literature	368	.22	70	Longitudinal	Chile	-	Composite
51	51	Susperreguy et al.	2020	Published Literature	368	.02	70	Longitudinal	Chile	-	Magnitude Estimation

51	51	Susperreguy et al.	2020	Published Literature	368	-.08	70	Longitudinal	Chile	-	Magnitude Estimation
51	51	Susperreguy et al.	2020	Published Literature	368	-.05	70	Longitudinal	Chile	-	Operations
51	51	Susperreguy et al.	2020	Published Literature	368	.21	70	Longitudinal	Chile	-	Operations
52	52.1	Susperreguy et al.	2021	Published Literature	99	.11	57	Concurrent	Mexico	-	Composite
52	52.1	Susperreguy et al.	2021	Published Literature	99	.17	57	Concurrent	Mexico	-	Composite
52	52.2	Susperreguy et al.	2021	Published Literature	74	.01	56	Concurrent	Mexico	-	Composite
52.2	52.2	Susperreguy et al.	2021	Published Literature	74	.29	56	Concurrent	Mexico	-	Composite
53	53	Wei et al.	2020	Published Literature	173	.21	67	Longitudinal	China	-	Non-Symbolic
53	53	Wei et al.	2020	Published Literature	173	-.17	67	Longitudinal	China	-	Magnitude Estimation
53	53	Wei et al.	2020	Published Literature	173	.23	67	Longitudinal	China	-	Composite
53	53	Wei et al.	2020	Published Literature	170	.24	71	Longitudinal	China	-	Composite
53	53	Wei et al.	2020	Published Literature	165	.29	75	Longitudinal	China	-	Composite
54	54	Zhang et al.,	2020	Published Literature	196	.19	61	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	196	.16	61	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	196	.21	61	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	196	.19	61	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	196	.13	61	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	196	.12	61	Longitudinal	China	-	Composite

54	54	Zhang et al.	2020	Published Literature	196	.17	61	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	196	.15	61	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	179	.15	73	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	179	.06	73	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	179	.12	73	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	179	.12	73	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	179	.14	73	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	179	.07	73	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	179	.13	73	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	179	.13	73	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	152	.28	85	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	152	.23	85	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	152	.29	85	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	152	.31	85	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	152	.24	85	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	152	.22	85	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	152	.25	85	Longitudinal	China	-	Composite
54	54	Zhang et al.	2020	Published Literature	152	.29	85	Longitudinal	China	-	Composite

55	55	Blevins-Knabe et al.	1996	Published Literature	63	.01	67	Concurrent	United States	North America	Composite
56	56	Bennett	2017	Theses	68	.22	48	Concurrent	United Kingdom	United Kingdom	Composite
57	57	Ellis	2020	Grey Literature	51	.11	67	Longitudinal	United States	North America	Composite
57	57	Ellis	2020	Grey Literature	51	.26	67	Longitudinal	United States	North America	Composite
57	57	Ellis	2020	Grey Literature	51	.09	67	Longitudinal	United States	North America	Composite
57	57	Ellis	2020	Grey Literature	51	.11	67	Longitudinal	United States	North America	Composite
57	57	Ellis	2020	Grey Literature	51	.06	73	Longitudinal	United States	North America	Composite
57	57	Ellis	2020	Grey Literature	51	.13	73	Longitudinal	United States	North America	Composite
57	57	Ellis	2020	Grey Literature	51	.03	73	Longitudinal	United States	North America	Composite
57	57	Ellis	2020	Grey Literature	51	.10	73	Longitudinal	United States	North America	Composite
57	57	Ellis	2020	Grey Literature	51	.25	73	Longitudinal	United States	North America	Magnitude Estimation
57	57	Ellis	2020	Grey Literature	51	-.13	73	Longitudinal	United States	North America	Magnitude Estimation
57	57	Ellis	2020	Grey Literature	51	.18	73	Longitudinal	United States	North America	Magnitude Estimation
57	57	Ellis	2020	Grey Literature	51	.01	73	Longitudinal	United States	North America	Magnitude Estimation
58	58	Niklas & Schneider	2017	Grey Literature	125	.12	66	Longitudinal	Germany	Europe (exclude UK)	Composite
58	58	Niklas & Schneider	2017	Grey Literature	125	.07	70	Longitudinal	Germany	Europe (exclude UK)	Composite
58	58	Niklas & Schneider	2017	Grey Literature	125	.05	74	Longitudinal	Germany	Europe (exclude UK)	Composite

58	58	Niklas & Schneider	2017	Grey Literature	125	.04	70	Longitudinal	Germany	Europe (exclude UK)	Composite
58	58	Niklas & Schneider	2017	Grey Literature	125	.01	74	Longitudinal	Germany	Europe (exclude UK)	Composite
58	58	Niklas & Schneider	2017	Grey Literature	125	.00	74	Longitudinal	Germany	Europe (exclude UK)	Composite
59	59	Niklas et al.	2020	Grey Literature	179	.25	64	Longitudinal	Germany	Europe (exclude UK)	Composite
59	59	Niklas et al.	2020	Grey Literature	181	.26	70	Longitudinal	Germany	Europe (exclude UK)	Composite
59	59	Niklas et al.	2020	Grey Literature	177	.19	70	Longitudinal	Germany	Europe (exclude UK)	Composite
60	60	Niklas et al.,	2020	Grey Literature	305	.19	59	Concurrent	Germany	Europe (exclude UK)	Composite
61	61	Napoli & Purpura	2021	Grey Literature	42	.39	47	Concurrent	United States	North America	Composite
61	61	Napoli & Purpura	2021	Grey Literature	42	.28	47	Concurrent	United States	North America	Composite
62	62	Matthew et al.	-	Grey Literature	57	.35	71	Concurrent	United States	North America	Composite
62	62	Matthew et al.	-	Grey Literature	57	.23	71	Concurrent	United States	North America	Composite
62	62	Matthew et al.	-	Grey Literature	57	.38	71	Concurrent	United States	North America	Composite
62	62	Matthew et al.	-	Grey Literature	57	.27	71	Concurrent	United States	North America	Composite
62	62	Matthew et al.	-	Grey Literature	57	.45	71	Concurrent	United States	North America	Composite
62	62	Matthew et al.	-	Grey Literature	57	.26	71	Concurrent	United States	North America	Composite
63	63	Collins	2016	Published Literature	86	.16	53	Concurrent	United States	North America	Number Knowledge
63	63	Collins	2016	Published Literature	86	.12	53	Concurrent	United States	North America	Number Knowledge
63	63	Collins	2016	Published Literature	86	.03	53	Concurrent	United States	North America	Magnitude Estimation

63	63	Collins	2016	Published Literature	86	-.01	53	Concurrent	United States	North America	Non-Symbolic
63	63	Collins	2016	Published Literature	86	.11	53	Concurrent	United States	North America	Operations
64	64	Cankaya	2013	Published Literature	42	-.06	59	Concurrent	Canada	North America	Counting
64	64	Cankaya	2013	Published Literature	42	.00	59	Concurrent	Canada	North America	Number Knowledge
64	64	Cankaya	2013	Published Literature	42	.19	59	Concurrent	Canada	North America	Number Knowledge
64	64	Cankaya	2013	Published Literature	42	.07	59	Concurrent	Canada	North America	Non-Symbolic
65	65	Cankaya	2013	Published Literature	118	-.11	47	Concurrent	Canada & Turkey	-	Counting
65	65	Cankaya	2013	Published Literature	118	.08	47	Concurrent	Canada & Turkey	-	Number Knowledge
65	65	Cankaya	2013	Published Literature	118	.25	47	Concurrent	Canada & Turkey	-	Number Knowledge
65	65	Cankaya	2013	Published Literature	118	.29	47	Concurrent	Canada & Turkey	-	Number Knowledge
65	65	Cankaya	2013	Published Literature	118	.10	47	Concurrent	Canada & Turkey	-	Non-Symbolic
66	66	Trickett et al.	2021	Grey Literature	164	.03	44	Concurrent	United Kingdom	United Kingdom	Number Knowledge
66	66	Trickett et al.	2021	Grey Literature	164	.02	44	Concurrent	United Kingdom	United Kingdom	Magnitude Estimation
66	66	Trickett et al.	2021	Grey Literature	164	.16	44	Concurrent	United Kingdom	United Kingdom	Number Knowledge
66	66	Trickett et al.	2021	Grey Literature	164	.18	44	Concurrent	United Kingdom	United Kingdom	Number Knowledge
66	66	Trickett et al.	2021	Grey Literature	164	-.04	44	Concurrent	United Kingdom	United Kingdom	Counting
66	66	Trickett et al.	2021	Grey Literature	164	.13	44	Concurrent	United Kingdom	United Kingdom	Operations
67	67	James-Brabham et al.	2021	Grey Literature	69	-.10	44	Concurrent	United Kingdom	United Kingdom	Counting

67	67	James-Brabham et al.	2021	Grey Literature	69	.10	44	Concurrent	United Kingdom	United Kingdom	Number Knowledge
67	67	James-Brabham et al.	2021	Grey Literature	69	-.11	44	Concurrent	United Kingdom	United Kingdom	Composite
68	68	James-Brabham et al.	2021	Grey Literature	106	.11	45	Concurrent	United Kingdom	United Kingdom	Composite
69	69	van Herwegen & Donlan	-	Grey Literature	82	.12	44	Concurrent	United Kingdom	United Kingdom	Composite

Note. *r* refers to the correlation coefficient between frequency of home mathematical activities and mathematical ability.