Social inequalities in executive function development and attainment during adolescence: An examination of longitudinal relations in the Study of Cognition, Adolescents and Mobile Phones

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Signed declaration

I, Roisin Carlotta Perry, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed: REDACTED Date: 07.03.2024

Covid impact statement

This PhD project was significantly impacted by delays in the transfer of data from Department for Education as a result of the Covid-19 pandemic. I did not receive the National Pupil Database (NPD) data until the summer of my second year of study, which meant that I was unable to run the analyses for the main study in this thesis (**Chapter 4**) until two thirds of the way through my degree. Further analyses looking at the role of mobile phone use and health behaviours in explaining executive function to attainment relationships were planned (see **Covid Impact Appendix: Appendix A**) but were not feasible to complete within the timeframe of the degree.

In response to these delays to data access, I carried out the study described in **Chapter 3,** which was not one of the original studies planned for this thesis. After writing this study, I decided to change the focus of the thesis to have a stronger emphasis on socioeconomic status. I began this piece of work in my second year and, on receiving the NPD data, I reran the analyses to include Free School Meals status as I felt that it was important that the models reflected comprehensive measures of socioeconomic status.

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Abstract

By the end of primary school, the poorest pupils in the UK are around a year behind their peers in terms of educational attainment. This gap doubles by the age of 16. Socioeconomic gradients in executive function skills are also widely reported. However, no studies have explored whether gaps in executive function skills widen during adolescence and, if they do, whether these are associated with (and are therefore a potential cause of) the widening socioeconomic gradient in attainment. This thesis presents the results of a series of analyses of longitudinal data from the demographically representative Study of Cognition, Adolescents and Mobile Phones (SCAMP; n = 2,726) linked with data from the UK Department for Education's National Pupil Database. In a first study, I show that social inequalities in working memory skills (but not cognitive flexibility or inhibition) show small but significant increases between 12-14 years of age. Unpacking the correlated measures used to index socioeconomic status, parental occupation and Free School Meals status, but not neighbourhood deprivation or parental education, predicted widening gaps in executive function over adolescence. The second study demonstrated that the widening socioeconomic status gradient in attainment over adolescence was significantly predicted by widening gaps in working memory skills. Change in verbal working memory span between 12-14 years partly mediated socioeconomic gradients across the core subjects, but the development of visuospatial working memory skills only partly mediated socioeconomic gradients in maths and science. These results challenge the idea that executive function skills are only relevant for attainment during primary education and provide an important starting point for understanding different ways in which socioeconomic status might impact on attainment during adolescence.

Impact statement

The work presented in this thesis provides and tests an explanation for the widening socioeconomic gradient in educational attainment between ages 11 and 16 that is observed in the UK (Education Policy Institute, 2023). I show that, over a two-year period, there is a small but significant increase in social inequalities in working memory skills. I then show that widening social inequalities in working memory are related to widening inequalities in attainment over adolescence. Results held controlling for demographic factors and school quality, ruling out the possibility that correlations between socioeconomic status and demographic factors explain the relationship of socioeconomic status with working memory development and attainment.

I also show that grouping socioeconomic, executive function or attainment measures can result in missing important nuance and therefore to inaccurate conclusions. The clearest example was that a model treating all three constructs as latent factors suggested that socioeconomic status was not significantly related to executive function or attainment change, but a model looking at specific socioeconomic status effects showed this was only true for area deprivation; household poverty, parental occupation and parental education predicted change in attainment. The former two indicators also predicted change in scores on working memory measures over adolescence. These findings show that there are multiple statistical pathways from socioeconomic status to attainment, consistent with the possibility of diverse causal pathways.

These findings have several important theoretical implications. First, they provide the strongest rebuttal to date of the theory that the impact of executive function skills on attainment *fades out* during adolescence (Stipek & Valentino, 2015). Second, it has been suggested that executive function to attainment relations can be entirely attributed to the covariance of executive function with socioeconomic status and earlier attainment (Jacob &

Parkinson, 2015). Since I controlled for attainment and executive function measures taken at the same time as socioeconomic status, I was able to rule out the possibility that executive function is just a proxy for these background characteristics. Third, my analyses isolated contributions of individual aspects of socioeconomic status to different executive function skills and school subjects. These findings narrow the pool of likely causal explanations for social inequalities in educational attainment and may help to guide interventions to reduce inequalities.

The effect of low attainment during adolescence is consequential to life outcomes, limiting an individual's post-16 educational and career opportunities. My results suggest that social inequalities in cognitive and academic outcomes not only persists into adolescence but widen, suggesting an accumulating effect of socioeconomic status over time. This is of clear policy relevance. My findings add to a growing body of literature suggesting that the nature of academic support needed may depend on an individual's specific socioeconomic circumstances. While future experimental studies may establish that working memory is a viable intervention focus, the associations between working memory and attainment noted here were small. Social inequalities in attainment are likely best explained by multiple cognitive, social and emotional factors and focusing on working memory alone is likely to have only modest effects.

Table of Contents

Signed declaration 2
Covid impact statement 2
Acknowledgements 3
Abstract 4
Impact statement 5
Table of Contents 7
List of Figures 11
List of Tables 13
List of abbreviations 14
Chapter 1: Introduction 15
1.1 Structure of this chapter 18
1.2 Definitions 19
1.2.1 Executive function 19
1.2.2 Socioeconomic status 22
1.3 Theoretical framework 24
1.4 Narrative review of reviews 28
1.4.1 Socioeconomic status and attainment 28
1.4.2 Socioeconomic status and executive function 35
1.4.3 Executive function and attainment 36
1.5 Does executive function explain socioeconomic gradients in attainment? 39
1.6 Lessons learnt 41
1.7 What is already known about adolescence? 44
1.8 Aims 50
1.9 Thesis structure 52
1.9.1 Chapter 2: General methodology 52
1.9.2 Chapter 3: Longitudinal associations between socioeconomic status and executive function during adolescence are small and specific 53
1.9.3 Chapter 4: The widening socioeconomic status gradient in attainment over adolescence is related to widening gaps in working memory skills 53
1.9.4 Chapter 5: Conclusions 54
Chapter 2: General methodology 55
2.1 About the Study of Cognition, Adolescent and Mobile Phones 56
2.1.1 Linkage with National Pupil Database data 57

2.2 Participants 59
2.2.1 Data loss from linkage and cleaning 61
2.2.2 Selection based on school type 61
2.2.3 Included participants 62
2.3 Measures 68
2.3.1 Socioeconomic status indices 68
2.3.2 Executive function measures 70
2.3.3 Educational attainment measures 75
2.3.4 Control variables 81
2.4 Procedure 85
2.5 Modelling approach 87
2.5.1 Missing data 87
2.5.2 Running regression models using lavaan's sem() function 94
2.5.3 Why use linear models? 95
2.6 Data cleaning and assumption checks 95
2.6.1 Assessing the distribution of continuous variables 96
2.6.2 Treatment of non-continuous variables 99
2.6.3 Accounting for clustering in the sample 101
2.7 Assessing model fit 103
Chapter 3: Longitudinal associations between socioeconomic status and executive function during adolescence are small and specific 104
3.1 Introduction 105
3.1.1 Socioeconomic status and executive function in adolescence 107
3.1.2 Aims and hypotheses 111
3.2 Methods 112
3.2.1 Analysis plan 112
3.2.2 Other cognitive measures 114
3.2.3 Confirmatory Factor Analysis 115
3.3 Results 117
3.3.1 Descriptives 117
3.3.2 Correlation analyses 118
3.3.3 Model 1. Testing for general effects of socioeconomic status on executive function 121
3.3.4 Model 2. Testing for differential relations between socioeconomic status indices and executive function 124

3.3.5 Model 3. Testing sensitivity of different executive function measures to socioeconomic status 126
3.3.6 Model 4. Associations of individual socioeconomic status indices with performance on individual executive function measures 129
3.4 Discussion 132
3.4.1 Results summary 132
3.4.2 Consistency with the wider literature 133
3.4.3 Strengths and limitations 139
3.4.4 Conclusions 140
Chapter 4. The widening socioeconomic status gradient in attainment over adolescence is related to widening gaps in working memory skills 142
4.1 Introduction 143
4.1.1 Social inequalities in executive function and attainment in adolescence 146
4.1.2 What is so special about working memory? 148
4.1.3 Aims and hypotheses 150
4.2 Methods 151
4.2.1 Additional measure – school quality 151
4.2.2 Data preparation and assumption checks 152
4.2.3 Analysis plan 157
4.3 Results 159
4.3.1 Descriptives 159
4.3.2 Correlations and assumption checks 161
4.3.3 Model 1. Latent change model testing whether socioeconomic status and working memory predict GCSE attainment controlling for age 11 attainment. 163
4.3.4 Model 2. Testing for specificity of working memory to attainment relationships. 166
4.3.5 Model 3. Testing for specificity of socioeconomic status associations with attainment and working memory 172
4.3.6 Mediation analysis 178
4.3.7 Controlling for school quality 181
4.4 Discussion 184
4.4.1 Results summary 184
4.4.2 Consistency with the wider literature 187
4.4.4 Strengths and limitations 196
4.4.5 Conclusions 197
Chapter 5: Conclusions 199

5.1 General reflections 202
5.2 Strengths and limitations 205
5.3 Directions for future research 209
References 212
Covid impact Appendix 260
Appendix A 261
Chapter 2 Appendix 264
Appendix A 265
Appendix B 273
Appendix C 276
Appendix D 278
Chapter 3 Appendices 279
Appendix A 280
Appendix B 282
Appendix C 283
Appendix D 284
Appendix E 284
Chapter 4 Appendices 285
Appendix A 286
Appendix B 287
Appendix C 287
Appendix D 288
Appendix E 289
Appendix F 290
Appendix G 292

List of Figures

1.1 Ecological Systems Theory model

2.1 Map of schools in the Study of Cognition, Adolescents and Mobile Phones

2.2 Flow chart of the selection process of the analytic sample

2.3 Sociodemographic composition of the subsample

2.4 Executive function tasks

2.5 Relationship between socioeconomic status and executive function by ethnicity group

2.6 Relationship between socioeconomic status and educational attainment by ethnicity group

2.7 Socioeconomic status distribution by ethnicity group

2.8 Missing data plot

2.9 Distribution of scores on different executive function measures

2.10 Socioeconomic status distribution by school

3.1 Socioeconomic status and executive function factors

3.2 Widening social inequalities in executive function over adolescence

3.3 Beta coefficients for model 1, study 1

3.4 Beta coefficients for model 2, study 1

3.5 Beta coefficients for model 3, study 1

3.6 Beta coefficients for model 4, study 1

4.1 Number of pupils by school quality

4.2 Socioeconomic status, working memory and attainment factors

4.3 Directed acyclic graph

4.4 Average attainment at age 11 and age 16

4.5 Betas for socioeconomic status and age 11 attainment predicting age 16 attainment

4.6 Path diagram of model 1, study 2, with standardised betas

4.7 Path diagram of model 2, study 2

4.8 Path diagram of key paths in model 2, study 2, with standardised betas

4.9 Path diagram of model 3, study 2

4.10 Path diagram of key paths in model 3, study 2, with standardised betas

4.11 Path diagrams of mediation analyses

4.12 Mediation ratios by working memory measure and school subject

4.13 Path diagram of model 1, study 2, controlling for school quality

4.14 Path diagram of model 2, study 2, controlling for school quality

List of Tables

2.1 Subsample and full cohort demographics

2.2 SAT reading assessment focuses

2.3 Age 11 teacher assessed writing assessment focuses

2.4 Patterns of missingness in the dataset

2.5 Likelihood ratio tests

3.1 Average scores on different executive function measures

3.2 Correlation matrix for T1 measures

3.3 Correlation matrix for T2 measures

3.4 Model 1, study 1 beta estimates

3.5 Model 2, study 1 beta estimates

3.6 Model 3, study 1 beta estimates

4.1 Average socioeconomic status and attainment by ethnicity and first language status

4.2 Correlation matrix for key variables in study 2

4.3 Model 1, study 2 beta estimates

4.4 Model 2, study 2 beta estimates for variables regressed onto T2 working memory

4.5 Model 2, study 2 beta estimates for variables regressed onto age 16 attainment

4.6 Model 3, study 2 beta estimates for variables regressed onto age 16 attainment

4.7 Model 3, study 2 beta estimates for variables regressed onto T2 working memory

4.8 Mediation path coefficients

List of abbreviations

AX-CPT = AX-Continuous Performance Task

BDS = Backward Digit Span

CI = Confidence interval

CFI = Comparative Fit Index

CFT = Cattel's Culture Fair IQ Test

EF = executive function

FIML = Full Information Maximum Likelihood

GCSE = General Certificate of Secondary Education

IQ= Intelligence Quotient

M = Mean

NPD = National Pupil Database

Ofsted = Office for Standards in Education, Children's Services and Skills

PISA = Programme for International Student Assessment

RMSEA = Root Mean Square of Error Approximation

SAT = Standardised Assessment Test

SCAMP = Study of Cognition, Adolescents and Mobile Phones

SES = socioeconomic status

SD = Standard deviation

SWM = Spatial Working Memory Task

TLI = Tucker Lewis Index

TMT = Trail Making Task

UK = United Kingdom

US = United States

WM = working memory

Chapter 1: Introduction

"Adolescence is a dynamic maturational period during which young lives can pivot rapidly—in both negative and positive directions. Scientific progress in understanding adolescent development provides actionable insights into windows of opportunity during which policies can have a positive impact on developmental trajectories relating to health, education, and social and economic success" (Dahl et al., 2018).

Just over a decade ago, the UK government published two major reports – *The Foundation Years: Preventing Poor Children Becoming Poor Adults* (F. Field, 2010) and *Early Intervention: The Next Steps* (Allen, 2011) – both emphasising the importance of intervening in the early years to mitigate social inequalities in development and growth. These reports followed on from the *Zero to Three* movement in the US in the late 1990s. Allen, drawing on the Office for Economic Cooperation and Development (OECD, 2009) position, argued that investing in the development of young children is more likely to have positive impacts than investing in older children or adolescents. This widely held sentiment across nations is based on the idea that since the brain is nearly adult sized before children start formal schooling, most development must be complete by then (Allen, 2011; Giedd, 2002).

In actuality, the brain is highly plastic and important cognitive skills, and the brain regions that subserve them, continue developing through adolescence and beyond (Crone & Dahl, 2012; Ferguson et al., 2021; Murty et al., 2016). Moreover, the onset of adolescence represents the most significant period of cognitive development since early childhood (Fuhrmann et al., 2015). Therefore, adolescence can be viewed as both a window for increased opportunities for cognitive skill development but also a window of increased vulnerability (Furhmann et al., 2015). In line with this idea of increased vulnerability, national statistics indicate that social inequalities in attainment substantially increase over

adolescence (Education Policy Institute, 2023). In the UK, children living in persistent poverty are around a year behind their peers in terms of attainment by the end of primary school. This attainment gap widens to a distance equivalent to nearly two years by the end of secondary education. Whether this increasing gap is explained by increasing social inequalities in cognitive skills over adolescence has not previously been investigated. However, it is an important question to answer if we are to leverage the malleability of the adolescent brain as a second opportunity to level up social inequalities in educational attainment.

This thesis addresses this question, focusing on executive function skills. Executive function skills are a collection of cognitive processes that enable the enactment of goal directed behaviour (e.g., Miyake et al., 2000; see **1.2.1** for a more detailed description of executive function and its component cognitive processes). Individual differences in executive function skills are heritable (Friedman & Miyake, 2017), but also significantly related to socioeconomic factors (see Lawson et al., 2018; section **1.3.2**) and a large body of literature has accumulated showing that executive function skills are predictive of school attainment (e.g., for reviews see Cortés Pascual et al., 2019; Jacob & Parkinson, 2015; see sections **1.4.3**). Relative to other brain regions, a review of the neuroimaging literature showed that the development of brain regions involved in executive function also appear to be particularly sensitive to socioeconomic status (Noble et al., 2015).

Importantly, executive functions show some of the most protracted developmental trajectories of all cognitive skills, not reaching maturation until the mid-20s (Lee et al., 2013; Ferguson et al., 2021). There is an accelerated development of some executive function skills in early adolescence and continued linear improvement of others through adolescence (Aïte et al., 2018; Ahmed et al., 2022). Therefore, the development of executive function skills during

adolescence may reflect a particular strong case of vulnerability in the face of socioeconomic adversity.

In the decade that followed since the Field and Allen reports, the UK government have made significant investment in services and resources for young children, often by redirecting funding away from resources and services for older children and adolescents. For instance, all UK children in reception (4-5 years), years 1 (5-6 years) and 2 (6-7 years) have been eligible for free school meals since 2014. However, the upper threshold for claiming free school meals for children outside of these year groups has not increased since 2010. In other words, the funding for younger children has increased but investment in adolescence has not; not even to match the rate of inflation. Consequently, 69% (1.7 million) of children and adolescents whose parents receive universal credit cannot claim free school meals (Cribb et al., 2023). Further, since 2010/11, 70% of youth services (including 750 youth clubs; 4,500 youth workers) have also been cut (YMCA, n.d.) whilst spending on children and young people's services has increased as a whole. In parallel, over 20 years, a large volume of research into the association of socioeconomic status with cognitive development in young children has been published. However, such research focusing on adolescents is much rarer. To illustrate, in a meta-analysis of socioeconomic status - executive function associations in 2–18-year-olds (Lawson et al., 2018), only 3/33 studies included adolescent participants[1]. as Professor Jay Giedd (neuroscientist), put it: "Even though the first three years are important,

[1]This picture is beginning to change with the advent of the landmark longitudinal US *Adolescent, Brain and Cognitive Development* study (https://abcdstudy.org/), out of which cross-sectional studies of the relationship between socioeconomic status and brain/cognitive development are beginning to be published.

so are the next 16... I think that might have been somewhat overlooked with the emphasis on the early years" (Giedd, 2002).

Economics are not the focus of this thesis. Rather it sets out to further the evidence base on socioeconomic factors linked to cognitive and educational outcomes during adolescence in the UK to bring the support needs of low socioeconomic status individuals in this age group into sharper focus and, therefore, to inform future policy decisions. More specifically, this thesis describes the nature of social inequalities in executive function and attainment in UK adolescents, and the extent to which inequalities in executive function are related to inequalities in attainment.

Given the focus of my research on the UK context, I predominantly review research from the UK and the US. Although some important differences exist between these countries, which I return to consider in **5.1**, most of the research evidence on executive function and on social inequalities in cognitive development has been conducted in the US (see Lawson et al., 2018). Further, the sociopolitical conditions and, therefore the nature of poverty, in these two countries are relatively comparable (e.g., relative to the UK and countries in the Global South). I do not intend to make universal conclusions in this thesis but to present evidence relevant to UK policy makers. Hence, throughout, I explicitly state where the research I discuss was conducted if it was outside of the UK or US and, where relevant, reflect on the extent to which cultural or socioeconomic differences are likely to influence the comparability of previous findings to my own.

1.1 Structure of this chapter

In the following sections, I first define key terms, then outline my theoretical framework, then provide a narrative review of reviews on associations between socioeconomic status and educational attainment, associations between socioeconomic status

and executive function, and associations between executive function and attainment. Following this, I discuss the evidence from observational studies that executive function mediates socioeconomic gradients in pupil attainment and the evidence from intervention studies pointing to causal relations amongst these variables. I then outline lessons learnt from the mediation and intervention studies and the review of reviews. Next, I describe findings regarding social inequalities in executive function and attainment from three longitudinal cohort studies of adolescents and highlight the value of exploring relations between socioeconomic status and executive function in a new cohort of adolescents. Finally, the structure of the thesis and the research questions for the current piece of work are outlined.

1.2 Definitions

1.2.1 Executive function

Executive function is an umbrella term for a collection of mental processes subserved by the prefrontal cortex and recruited in everyday life when we need to execute our goals (Miyake et al., 2000; Salehinejad et al., 2021). Following Miyake et al. (2000), it is widely accepted that by adulthood there are at least three key executive functions. These are updating (also working memory or working memory updating) which involves online maintenance and use of information in memory; inhibition (also inhibitory control), the deliberate withholding of thoughts or actions when they are no longer adaptive; and shifting (also set-shifting or cognitive flexibility), the ability to dynamically shift between tasks, actions, and mental states.

The current prominent conceptualisation of executive function is that it comprises distinct, yet related processes. This is consistent with cognitive evidence (i.e., confirmatory factor analysis shows that executive functions are moderately correlated but separable abilities; Miyake et al., 2000; Friedman & Miyake, 2017), and neuroimaging evidence which suggests that Miyake's three core executive functions are subserved by three distinct but

overlapping frontoparietal networks (Logie, 2016). At the cognitive level, it has been suggested that attention may underpin all executive functions (McCabe et al., 2010), echoing early ideas about the central executive (e.g., Baddeley et al., 1986; 1996; Norman & Shallice, 1986). However, the notion that attention arises from interactions between different brain regions is coming to replace the early ideas about the central executive as a master brain/cognitive system which controls more passive systems (Logie, 2016).

There is, however, some debate in the literature about how many different executive processes should be distinguished (Doebel, 2020). This is partly due to differences in how executive function and its component processes are defined across disciplines, leading to conceptual confusion (Morrison & Grammer, 2016). Morris and Grammer highlight the notable example of whether self-regulation (a term used by developmental psychologists to describe children's control of their automatic reactions to the environment; e.g., Rothbart et al., 2013) should be thought of as a distinct concept from executive function (a term used by education researchers who tend to adopt the Miyake et al., 2000 framework). Another reason for differing conceptualisations between researchers is likely to be due to measurement choices. Questionnaire based measures of every day executive function tend to correlate only weakly with task-based measures, especially in younger populations (Snyder et al., 2021), and a wealth of executive function measures exist with varyingly convincing psychometric properties (e.g., Nyongesa et al., 2019).

Whilst it is beyond the scope of this thesis to review the theoretical debates about the structure of executive function at length, it is worth noting that skills such as planning and sustained attention are also frequently grouped under the umbrella of executive function (e.g., Donati et al., 2019) albeit far less frequently than working memory, inhibition, and cognitive flexibility. Doebel (2020) reminds us that Miyake's executive functions were yielded from

confirmatory factor analysis – they selected three executive functions out of practicality and their analyses may have supported more executive functions had they included more.

Some researchers refer to working memory, inhibitory control and cognitive flexibility (and sometimes planning and sustained attention) collectively as the "cool executive functions" which they distinguish from more emotionally or motivationally driven cognitive processes – the "hot executive functions" (Zelazo & Müller, 2002). Cool executive functions are thought to be recruited in affectively neutral situations, whereas hot executive functions are recruited in high stakes or affectively charged situations (Zelazo & Carlson, 2012). Whilst cool executive functions develop linearly from childhood to adulthood, hot executive functions take an inverted U-shape trajectory and dip during adolescence (Aïte et al., 2018). Many overlapping brain regions are recruited when individuals engage in hot and cool executive function tasks. However, lesion studies show that hot and cool executive functions are dissociable at the brain level (see Zelazo & Carlson, 2012). There is thought to be greater involvement of the orbitofrontal, ventral anterior cingulate and posterior cingulate cortices in hot executive function and of lateral prefrontal cortex and dorsal anterior cingulate cortex in cool executive function (Salehinejad et al., 2021). Further, at the behavioural level, research in typically developing populations shows that hot and cool skills are not correlated from adolescence onward (Aïte et al., 2018).

Studies looking at hot and cool executive function skills frequently only observe social inequalities in the latter; it has been suggested that the development of hot skills is more sensitive to emotional hardship than socioeconomic hardship (Backer-Grøndahl & Nærde, 2017; Finch & Obradović, 2017; Li-Grining, 2007). It therefore seems unlikely that individual differences in hot executive function skills would contribute to the socioeconomic gradient in attainment. Cool executive functions have been far more frequently researched in the context of school attainment and evidence regarding their links to socioeconomic status is

far less controversial. Tasks measuring hot executive function skills like the Marshmallow Task (Mischel, 1974), a measure of delay of gratification, can be criticised for confounding the adaptive scarcity mindset of children growing up in poverty with a failure to self-regulate effectively (e.g., Tunney & James, 2022). Moreover, in a study of five-year-old children from low income families, Duran and Grissmer (2020) showed that children who chose immediate rewards over delayed gratification had better executive function skills, as measured by the Head-Toes-Knees-Shoulders task (Ponitz et al., 2008), and were rated as better behaved by their teachers and peers. I therefore focus specifically on cool executive function and henceforth *executive function* is used to refer just to these processes.

Consistent with the weight of the evidence and the consensus amongst researchers (Miyake et al., 2000; Friedman & Miyake, 2017), I assume that executive functions are separable but related processes. I label tasks as measures of the skill domain they are most often described as tapping; however, I acknowledge that these tasks are not pure measures of these skills. I attempt to isolate different executive functions in **Chapters 2** and **3** and discuss the limitations of work that does not control for other aspects of executive function or cognition when making claims about the specificity of associations between socioeconomic status, executive function, and attainment in sections **1.6** and **5.2**. The working memory, planning, shifting and inhibitory control measures used in the empirical chapters of this thesis were the executive function measures available in the secondary dataset I made use of (see section **1.8** for detail on why these measures were included in the cohort study).

1.2.2 Socioeconomic status

Exactly what high and low socioeconomic status look like differs markedly internationally (Mousavi et al., 2022). In the developmental literature, child socioeconomic status is most often indexed by their parents' education levels or their household income (e.g., see Lawson et al., 2018). Parental occupation and area level deprivation are also used as

indicators of child socioeconomic status, albeit less frequently. Equally, there are many different definitions of socioeconomic status. However, these generally centre on two key ideas: that socioeconomic status pertains to 1. disparities between individuals 2. in access to resources/opportunities (e.g., Ross & Mirowsky, 2008; Farah, 2017).

Typically, socioeconomic status is indexed as parental education, parental occupation, household income, area level deprivation, or a combination of these factors (see sections **1.4.1** and **1.4.2** for reviews). Bukodi and Goldthorpe (2013) suggest that the first index can be viewed a marker for educational resources, including learning resources in the home and capacity to support the child with their learning and in navigating the education system. When modelled together, they suggest that parental occupation indexes sociocultural resources (e.g., social networks, parental and cultural values and expectations, engagement with culturally enriching activities), linking this to the concept of social class, and that household income acts a marker of financially determined resources (e.g., nutrition pre- and post-natally, extra-curricular activities and tutoring). Meanwhile, neighbourhood level socioeconomic status can be thought of as an index of access to services (e.g., healthcare, high quality schools; Shucksmith et al., 2023). This framework highlights some processes through which socioeconomic status is thought to be related to executive function and attainment: through its relationship with individual differences in cognitive stimulation, nutrition and health (Farah, 2017; Thomas & Coecke, 2023).

However, beyond its associations with access to resources and services, socioeconomic status is correlated with multiple other factors linked to cognitive and academic difficulties (see Farah, 2017; Thomas & Coecke, 2023 for reviews). Maternal stress and exposure to ingested and environmental toxins have been shown to have damaging impacts on fetal brain development. The first two factors are typically thought of as being related to financial circumstances (e.g., Thomas & Coecke, 2023) and the latter to

neighbourhood socioeconomic status, particularly in urban areas (Milojevic et al., 2017). Postnatally, parenting behaviours and parental stress have been linked to higher scores on cognitive and attainment measures (Farah, 2017; Thomas & Coecke, 2023) and are linked to education and income, respectively (Davis-Kean et al., 2019). Consistent with the extant evidence, in this thesis, I assume that the mechanisms explaining social inequalities in executive function and attainment are linked to such factors (objective socioeconomic status effects) and not a result of the psychosocial stress of social comparison based on socioeconomic factors (subjective socioeconomic status effects).

Rather than focusing on socioeconomic status linked factors, this thesis is primarily concerned with research into the relationship between socioeconomic status indicators and cognitive and academic outcomes. This type of research moves the focus from individual families to systemic inequalities in access to resources and opportunities that can be targeted via policy changes (Kuchirko, 2019; Pecukonis et al., 2024). Moreover, more observational research is needed to reliably map out possible pathways from socioeconomic status to attainment during adolescence before we can begin to understand which of the many possible family and environmental factors that covary with socioeconomic status might explain social inequalities in educational attainment. In other words, further observational research is needed to inform intervention and experimental lab-based studies testing causal explanations of adolescent social inequalities in attainment.

1.3 Theoretical framework

This thesis draws on theories from neuroscience, sociology, and psychology. Broadly, I take a Neuroconstructivist perspective (Karmiloff-Smith, 2009). Neuroconstructivism is an overarching theory of brain and cognitive development, typically reserved as a framework for explaining divergent developmental trajectories in neurodevelopmental conditions. However, it has recently been applied to explain individual differences in cognitive skills in typically

developing populations (Rinaldi & Karmiloff-Smith, 2017). This framework suggests that there are biological constraints which underpin brain development, but that these are weak, so the environment a child grows up in can have substantial impacts on cognitive development. This approach also proposes that the developing brain influences its environment. For example, a pupil from a disadvantaged family has less access to cognitively stimulating activities and more exposure to stress and pollution which have negative impacts on cognitive development. As a result, this pupil has weaknesses in some cognitive skills and finds cognitively challenging activities aversive. They are therefore less inclined to seek out and engage in such activities even though these activities are likely to benefit their cognitive development, compounding the pre-existing inequalities between them and their more affluent peers.

At a more specific level, this thesis is influenced by cognitive adaptation approaches, such as those put forward by Mittal et al. (2015) and Frankenhuis and Nettle (2020). These argue that the way cognitive skills develop under conditions of adversity should be viewed as an adaptive response to environmental pressures. These approaches posit that skills relevant to functioning in one's environment are heightened during development, but this may be at the expense of the development of other cognitive skills. However, skills that are optimized for functioning in a stressful home environment or neighbourhood may not necessarily be conducive to functioning in an environment with different pressures (Frankenhuis et al., 2016). For example, a child growing up in a dangerous neighbourhood may become hyperattentive to changes in noise in the environment which makes them appear distractable in the classroom and causes them to miss out on key information. Such explanations can more readily account for the finding that some cognitive skills are heightened in individuals who grew up in stressful circumstances (Mittal et al., 2015) and that experience of poverty is not associated with the same extent of cognitive difficulties in different groups of children

(Howard et al., 2020). Like neuroconstructivism, these approaches also encourage us to "Embrace Complexity!" (Karmiloff-Smith, 2017, pp. 386) and question what it means to be advantaged or disadvantaged when thinking about different developmental outcomes.

In trying to map out and explain different possible pathways from socioeconomic status to executive function and attainment, this thesis is also heavily influenced by socioecological approaches, such as Bronfenbrenner's (2005) Ecological Systems Theory. These frameworks consider the proximity of different influences for the pupil and distinguish between factors that directly influence them (e.g., family, school, peers) and more distant systems (e.g., education policy) which will have indirect effects via the systems that are closer in proximity to the pupil (see **Figure 1.1** for a contemporary version of the Ecological Systems Theory model). In this thesis, I primarily focus on factors within adolescents' microsystem and how these might relate to their cognitive and educational development. However, I regularly reflect on how the microsystems might be influenced by wider sociocultural and political factors.

Figure 1.1.

An Ecological Systems Theory model of factors influencing pupils in the 21st century, hand drawn by the author of this thesis.

REDACTED

Note. To appear in Perry, R. C., Bowen, A. E. J., Palmer, L. R. J., & Thomas. (In press). Overview and synthesis of the Science of Learning landscape: Bridging interdisciplinary divides. In W. L. D. Hung, A. Jamaludin, & J. S. Huang (Eds.), *Scaling System-Wide Education Change in Learning - Convergence of Learning Sciences, Science of Learning, and Science of Systems.*

1.4 Narrative review of reviews

The following section gives a narrative review of review articles published in peer reviewed journals on relationships between 1) socioeconomic status and attainment, 2) socioeconomic status and executive function, 3) executive function and attainment. Reviews were identified by searching Psycinfo, Embase, and Medline, with a final search of all databases carried out in January 2023. I searched for articles published in English, focusing on typically developing infants, children, or adolescents[2]. In this section, I focus specifically on reviews dealing with observational studies, as the aim of overviewing these publications was to identify guiding principles that the studies presented in this thesis, which also use observational data, should follow. I also focus specifically on studies of individual level socioeconomic status, as opposed to school socioeconomic status or peer socioeconomic status given the aims of the present studies. In the proceeding section, I then discuss the evidence that the relationships reported in reviews of observational studies are causal.

1.4.1 Socioeconomic status and attainment

The first reviews focusing on the relationship between socioeconomic status and educational attainment were published in the early 1980s (Bond, 1981; White, 1982). These and all subsequent reviews (Banerjee, 2016; Early, 2020; Sirin, 2005; Selvitopu & Kaya, 2021; Li et al., 2023; Liu et al., 2020) concluded that there is a significant moderate sized positive association between socioeconomic status and attainment. In this section, I review the average effect sizes, moderators and mechanisms identified through 40 years of research into social inequalities in attainment.

Effect sizes and moderators

[2] Studies including studies on both typically developing pupils and pupils with Special Educational Needs and Socioemotional and Mental Health needs were included.

White (1982) meta-analysed 143 studies published in books and journals between 1918-1975 and unpublished sources. They observed an overall correlation of $r = .25$ between socioeconomic status and attainment (measured at the student level) and showed that grade level of pupils, the index of socioeconomic status used, and type of attainment measure used influenced effect sizes (but note that they do not detail the statistical significance of these results). Specifically, higher grade levels were associated with smaller effects of socioeconomic status on attainment, possibly partly due to low achieving pupils leaving school earlier. Home environment measures were most strongly associated with attainment, followed by household income, parental occupation, and then parental education, looking at individual indicators of socioeconomic status as predictors (although the author disputes the use of home environment as a metric of socioeconomic status indicator). However, studies looking at multiple indicators tended to have the largest effects. Similarly, effects of socioeconomic status on IQ, then composite achievement measures were largest, and this was followed by verbal attainment measures, then maths. White also found, that samples with restricted variability in socioeconomic status or attainment produced lower estimates for the effect of socioeconomic status on attainment.

Sirin (2005) conducted an updated meta-analysis of 58 US studies (with data from 75 different samples) published between 1990-2000, criticising White's (1982) use of unweighted correlations in effect size calculation, their treatment of multiple correlations from the same study as independent effects, and their use of IQ as an attainment measure. Despite the limitations of the earlier review, Sirin observed similar sized effects ($r = .27$-$.28$) and replicated the finding that the type of socioeconomic status index used moderated the effect size. Again, they found that socioeconomic status indicators more proximal to the pupil; here educational resources in the home and access to services outside of school, were significantly better predictors of attainment than parent education, income, occupation, and

neighbourhood deprivation. In this review, differences between parent education, income and occupation were not significant. However, studies looking at neighbourhood level deprivation as a predictor observed significantly smaller effects on attainment than studies using parental education and income as predictors, and free/reduced price lunches had significantly larger effects on attainment than other income indices, parental education, parental occupation, and neighbourhood deprivation.

Sirin (2005) also found that studies using dichotomous socioeconomic status indicators found smaller effect sizes. Further, parent reports of socioeconomic status generated the largest effects, then secondary reports and then pupil reports. At the outcome level, mathematics assessments saw the largest effects of socioeconomic status, then language assessments, science assessments, and use of general achievement measures tended to result in the smallest effects, contradicting the pattern observed by White (1982). All reporter and subject differences were statistically significant after Bonferroni adjustment. Analyses looking at pupil level differences as moderators showed, again in contrast to White, that the effects of socioeconomic status on attainment increase with grade level until late childhood.

In the past 10 years, a further four reviews have been published on this topic. Liu et al. (2020) meta-analysed 62 studies (78 independent samples; N = 215,649) published between 1979-2017 exploring socioeconomic status to attainment relationships in Chinese pupils, Early et al. (2020) conducted a narrative systematic review of 23 UK studies published between 2000-2012 focusing on Programme for International Student Assessment (PISA) scores, and Selvitopu and Kaya (2023) meta-analysed 48 studies (with no restriction on country; 62 independent samples; N = 386,601) published between 2010-2019. A further review looked at socioeconomic status as a predictor of attainment in a specific subject: Li et al. (2023) meta-analysed 381 studies published between 1985-May 2021 investigating the relationship between socioeconomic and reading attainment. All meta-analyses obtained

similar effect sizes (r = .22 - .27) of socioeconomic status on attainment which were consistent in size to the earlier reviews.

However, there was less consistency when looking at moderators of the association. Liu et al. (2020) found that time and school subject moderated the socioeconomic status-attainment association, with effect sizes decreasing over time and larger effects on language (Chinese or English) measures than maths/science and general attainment measures. Selvitopu and Kaya (2021) found completely opposing results to Liu et al. They showed a significant increase in effect sizes over time (although note that they included studies from a much shorter window of time) and, consistent with Sirin (2005) that maths outcome measures were associated with largest effect sizes, then language and then general attainment outcome measures. Overlapping CIs suggest that the maths – science and language – science differences were not significant in this review[3].

Liu et al.'s (2020) findings further differed from Sirin's (2005) in that they did not find that grade level or type of socioeconomic status indicator were significant moderators. How high stakes tests were also did not moderate the socioeconomic status to attainment effect. These results are, again, inconsistent with Selvitopu and Kaya (2021). Unlike both Liu et al. and Sirin, Selvitopu and Kaya showed that effects trended toward decreasing with grade level. However, in this review, the main effect of grade level was likely driven by their inclusion of studies looking at higher education which had an average effect size of r = .05, whilst effects from studies of pre-primary, primary and secondary pupils were all in the range of r = .26-.31. The small average effect in higher education studies is likely explained by range restriction in socioeconomic status, due to the substantial cost of higher education courses, and possibly also range restriction in attainment due to the academic selectivity of

[3] The authors did not report any contrasts between levels of their moderator variables.

universities. Looking at the average effect sizes for studies using different socioeconomic status indicators, parental occupation and composite measures had the largest effects, then measures of family resources, and finally parental education and income.

Early's (2020) systematic review of UK studies also seems to suggest that parental occupation is a particularly reliable positive predictor of reading and mathematics achievement. Whilst most studies also suggested a positive relationship between parental education and attainment, one study which compared parental education and occupation suggested that parental education was a worse predictor of PISA assessed reading and maths attainment. They also found that a composite measure of socioeconomic status was also a positive predictor of science and maths attainment in the few studies that used it.

The lack of consistency between these reviews regarding the significance of different moderators, despite all yielding similar effect size estimates for the relationship between socioeconomic status and attainment, can be put down to several factors. Selvitopu and Kaya (2021) show that the type of attainment measure used (e.g., effects of socioeconomic status are smaller on national exams compared to measures used in research) and the country in which the research was carried out significantly moderate the size of socioeconomic status to attainment associations. This latter point is particularly important, as the nature of poverty as well as economic trends differ markedly across countries. Therefore, inconsistencies between samples from different cultures are, to some extent, to be expected.

Mechanisms

Bond (1981) provides a narrative review focusing on four explanations for the widely reported association between socioeconomic status and attainment: 1) genetics, 2) cultural factors, 3) unequal educational experiences, and 4) schools as reproducers of structural social inequalities. Given the time in which the review was produced, the first explanation hails

from the eugenicist notion that some groups are genetically inferior to one another, and that the ability of pupils from deprived backgrounds to succeed academically is only limited by their innate talent. Bond thankfully dismisses the value of this explanation and society as a whole has tended to move away from this prejudicial and deterministic line of thought.

Recent studies show that polygenic scores predict only up to 10% of the variance in individual cognitive skills and up to 16% in educational attainment (Lee et al., 2018; Okbay et al., 2022; von Stumm et al., 2020) leaving substantial room for the environment to predict outcomes in both domains. Comparing adopted and non-adopted twins, Cheesman (2020) showed that the predictive strength of polygenic scores for attainment is halved in adopted twins, suggesting that a notable portion of widely reported genetic effects are due to passive gene environment correlations. Similar results were obtained by Allegrini et al. (2020) who showed that gene-environment correlations account for 40% of the effects of polygenic scores on attainment. Further, in a study that also looked at the contribution of polygenic scores to attainment, nearly double the amount of variance in educational achievement at age 16 was explained by socioeconomic status compared to genetics (von Stumm et al., 2020). However, it must be noted that gene-environment correlations also obscure interpretation in observational research in the reverse direction, albeit to a lesser extent, with Allegrini et al. showing that gene-environment correlations explain 18% of supposed environmental effects on attainment.

Bond (1981) then goes on to discuss theories positing differential socialisation of children depending on their family socioeconomic circumstance, with particular focus on differences in language use of working-class children. He mentions that such approaches are criticised for failing to take a developmental approach which focuses on the causes of social inequality in attainment and goes on to relate factors such as the living conditions and poor nutrition of children growing up in poverty to inequalities in attainment. In the third theme, Bond then

deals with the effects of schooling. He discusses that not only are children from lower socioeconomic status families more likely to be educated in crowded, underfunded schools with less qualified teachers, but their teachers' expectations about their academic potential and their own pessimistic ideas about their career prospects because of their background create self-fulfilling prophecies resulting in poor school attainment. Finally, he reviews theories suggesting that educational institutions help maintain social inequalities.

Nearly 30 years later, Banerjee (2016) came to many similar conclusions in a systematic review of the 34 studies published in English between 2005-2014 that focused on predictors of maths and science attainment in disadvantaged pupils. Note that disadvantaged in this paper referred to socioeconomic status but also ethnic minority status and non-native English speakers. The paper is included, nonetheless, as these characteristics are often linked to socioeconomic status and because many of the mechanisms discussed are relevant across marginalised groups. Both reviews primarily drew upon the results from observational studies. However, Banerjee also appealed to consistent quasi experimental and experimental evidence to support their mechanistic suggestions where this was available.

Again, this review cited studies identifying attitudes towards education, teacher expectations and access to worse quality schooling as factors linked to lower school achievement. Banerjee, like Bond (1981), identifies under-nutrition and food instability as mechanisms explaining the effect of socioeconomic status on attainment and goes one step further and suggests that this and higher rates of illness impact on attainment through their effects on cognitive development. The recent review also suggests that parenting (parental involvement in education), neighbourhood factors (through peer influence on risk and disruptive behaviour), and experience of discrimination are additional mediators of social inequalities in attainment.

1.4.2 Socioeconomic status and executive function

Comparatively few papers have examined or attempted to explain the relationship between socioeconomic status and executive function. Lawson et al. (2018) meta-analysed the literature on socioeconomic status-executive function associations published between 1980 and January 2013. They identified 33 studies, making use of 25 datasets (total N = 8,760 two-to-18-year old's). Their meta-analysis showed small to medium positive effects of socioeconomic status on executive function and that methodological characteristics of studies influenced the strength of the association. The extent of socioeconomic variability within study samples (as in White, 1982; Sirin, 2005), the number of executive function measures used, and the aspect of executive function measured were significant moderators of effect size. The number of socioeconomic status indicators used was also a marginally significant moderator of effect sizes. However, age range or mean age of the sample, the intended socioeconomic composition of the sample, how stringent the exclusion criteria applied were, gender composition, and the type(s) of socioeconomic status indicator used were not significant moderators.

Mousavi et al. (2022) then conducted a selective critical review of studies published up until 2021 (with most published after the upper cut off in Lawson et al., 2018) exploring socioeconomic status-executive function associations. They provide examples of inconsistencies between studies that look at specific associations of individual indices of socioeconomic status with executive function and studies that look at differential effects of socioeconomic status and subdivisions of executive function. They urge greater consideration of the cultural relativity of findings and suggest that socioeconomic differences across countries is one possible explanation for inconsistency between studies. In contrast to Lawson et al. (2018) who found no effect of the aspect of socioeconomic status measures,

they also argue that fractionating socioeconomic status can lead to more accurate conclusions about the relationship between socioeconomic status and executive function.

1.4.3 Executive function and attainment

Jacob and Parkinson (2015) conducted a meta-analysis of 67 studies into the relationship between executive function and attainment in 3–18-year-olds. An important finding from this review was that including suitable control measures reduced the effect sizes of executive function to school attainment associations and rendered approximately half of associations non-significant. Jacob and Parkinson particularly stressed the importance of controlling for socioeconomic status and prior attainment when looking at executive function to attainment associations. They argue that without these controls in place, we cannot rule out that executive function is simply acting as a proxy for such measures. This review also showed no significant difference between effect sizes for maths and reading overall (r = .31 versus r = .30) or depending on the aspect of executive function measured, nor did it find significant age effects, differences between task based or questionnaire-based measures or differences between cross-sectional and longitudinal studies. However, working memory and shifting measures were associated with reliably larger effects on reading than attention control.

Cortés Pascual et al. (2019) later meta-analysed the 19 studies (21 samples; N = 7,947) published in English between 2009-2018 on executive function to attainment (language and mathematics) associations in primary school pupils. They observed slightly larger effects than Jacob and Parkinson (2015), finding an overall effect of executive function on attainment of r = .37 and effects of r = .37 and r = .35 for maths and language, respectively. Similar results were observed when they looked just at working memory measures as predictors of attainment (r_{maths} = .37; $r_{language}$ = .33). Overlapping CIs in both cases suggest that the differences in effect sizes between maths and language were not

significant, as in Jacob and Parkinson. Again, age also did not moderate effect sizes in this review, a finding the authors put down to the narrow age range studies, but sex was a significant moderator with smaller effects seen in females.

Literacy

Several further reviews have focused on specific school subjects. Follmer (2018) carried out a meta-analysis of 26 studies published between 1996-2016 and 3 unpublished studies (total N = 6,673) into the relationship between executive function and reading comprehension from 6 years to adulthood. They found an overall effect size of r = .36 and showed that the aspect of executive function measured significantly affected effect size estimates. Studies that looked at working memory (r = .38), shifting (r = .39) and planning (r = .36) tended to show larger effects on attainment than studies looking at inhibition (r = .21) or sustained attention (r = .25) as predictors. This pattern of results is consistent with that seen in Jacob and Parkinson (2015). CIs were quite wide for many of the executive functions, but there appeared to be a reliable difference between working memory and inhibition in Follmer's review. Further, consistent with Jacob and Parkinson and Cortés Pascual et al. (2019), age was not a significant moderator. This review also found no effect of whether executive function measures were task or questionnaire based or whether standardised or research specific measures of reading comprehension were used.

Maths

Meta-analyses of executive function associations with maths attainment similarly suggest that working memory is a particularly good predictor of attainment. Friso-van den Bos et al. (2013) meta-analysed 111 studies (N = 16,921) on the relationship between different aspects of executive function and attainment in 4–12-year-old pupils published between 1993–2012. They separated executive function into the following components: Inhibition, shifting,

visuospatial working memory updating, visuospatial sketchpad, verbal working memory updating, and the phonological loop. Studies measuring verbal working memory updating demonstrated significantly stronger effects on maths (r = .38) than all other aspects of executive function. The two visuospatial working memory measures (both r = .34) were associated with the next strongest effects. Average effect sizes for studies utilising these predictors were significantly larger than the remaining aspects of executive function. Effect sizes for studies with phonological loop measures as a predictor (r = .31) were also significantly larger than for shifting (r = .28) and inhibition (r = .27). These results contrast with Jacob and Parkinson's (2015) findings.

These effect sizes and the general pattern of specificity in executive function to maths attainment associations observed by Friso-van den Bos et al. (2013) have been replicated by a subsequent review. Peng et al. (2016), in a meta regression analysis of 110 studies (829 effect sizes) testing working memory to maths attainment associations, found an overall effect of working memory on maths of r = .35. In this review, composite measures of working memory resulted in the largest effects, then verbal[4], then visuospatial working memory measures. However, as in Jacob and Parkinson's review, none of these differences were significant.

Both reviews into the association between executive function and maths attainment have also shown that the type of maths attainment measure used is a significant moderator. Across all the executive functions included in Friso-van den Bos et al. (2013), studies using more general tests of maths skills tended to have larger effect sizes then tests assessing skills in a particular mathematical domain. Approaching this question slightly differently, Peng et al. (2016) showed that measures of performance on word-based maths problems and whole

[4] Averaged across verbal and numerical working memory measures.

number calculations were associated with significantly greater working memory effects than geometry measures. No other contrasts were significant in this review. In Friso-van den Bos et al. (2013), age (lower effects with time for shifting and visuospatial sketchpad and higher for visuospatial updating), controlling for relevant demographic confounds (smaller effects), and time lag between measurements in longitudinal studies (smaller effects with greater lag) were also significant moderators for half of the executive functions looked at. These potential moderators were not explored by Peng et al. (2016).

1.5 Does executive function explain socioeconomic gradients in attainment?

All systematic reviews and meta-analyses described above found overall significant moderate positive associations, be they between socioeconomic status and attainment, socioeconomic status and executive function or executive function and attainment. But what is the evidence that executive function differences are part of a causal pathway from socioeconomic status to attainment?

Cross-sectional studies of pre-school (Blakey et al., 2020), primary school (Nesbitt et al., 2013; Poon et al., 2022), and cross-sectional studies sampling both children and adolescents (Chevalère et al., 2023; Ellefson et al., 2020; Lawson & Farah, 2017; Wexler et al., 2020), show that executive function partially mediates the association between socioeconomic status and attainment. Longitudinal studies following pupils from preschool to early primary school (Barnes et al., 2022; Ng et al., 2021; Waters et al., 2021), through middle school (Albert et al., 2020) and from pre-school to late secondary school (Deer et al., 2020) have reached the same conclusions. Albert et al. reported that executive function explained 37% of the effects of socioeconomic status on maths and 17% on reading attainment. Barnes et al. found slightly smaller, but still significant, effects of 11% on reading attainment. That longitudinal research has consistently observed significant mediation effects is suggestive of this being a causal pathway through which socioeconomic status is related to

attainment. However, to have greater certainty in inferences of causality, studies capturing naturally occurring changes in family socioeconomic situations or intervention studies (in which the variable of interest is manipulated and all else is held constant) are needed.

Financial donations to families have been shown to improve children's cognitive and academic outcomes, with higher quality evidence for benefits for attainment in adolescence (see Cooper & Stewart, 2013; 2017; Duncan et al., 2017 for reviews). Effect size estimates from randomised control trials and quasi experiments, which exploit exogenous changes in income, range from .05-.17 of a SD increase in overall attainment per $1,000 increase in annual household income (based on the value of a dollar in 2000; Cooper & Stewart, 2017). Studies that imbed executive function training within the wider learning context also tend to show benefits for attainment (see Peng & Swanson, 2022; Scerif et al., 2023 for reviews). Hedge's g/Cohen's d effect size estimates from randomised control trials of working memory training interventions with significant statistically significant effects on standardised exam performance ranged from modest to very large (0.47-1.30, average = 0.81; Peng & Swanson, 2022). These effects are considerably larger than the small to moderate effects reported in studies of executive function to attainment associations (e.g., Jacob & Parkinson, 2015), but note that randomised control trials in education are known to produce inflated effect size estimates (Sims et al., 2023). It is beyond the scope of this thesis to explore why isolated executive function interventions are less efficacious, but these findings nevertheless suggest that under some circumstances executive function skills do influence individual attainment. Further, there is extant evidence from quasi experimental studies and randomized control trials that at least some aspects of socioeconomic status can have a causal impact on child/adolescent cognitive and academic outcomes.

1.6 Lessons learnt

A key conclusion that can be drawn from the reviews, mediation and intervention studies discussed is that there is no consistent evidence that associations between socioeconomic status and executive function or between executive function and attainment are smaller in adolescence compared to childhood or infancy. In other words, it is just as important to understand social inequalities in executive function development and attainment in the teenage years as in the early years. We also know that social inequalities in attainment widen from age 11 and age 16 in the UK (Education Policy Institute, 2023). Therefore, further study of the interplay between socioeconomic status, executive function and attainment over adolescence is warranted in the context of the UK.

Most of the extant research is cross-sectional and observational, which obscures interpretations of causality. Logically, we know that pupil executive function skills and educational attainment are unlikely to influence family socioeconomic status whilst pupils are still in school, but the converse is a plausible causal story. However, we cannot rule out the possibility that it is educational attainment that influences executive function skills and not vice-versa from cross-sectional findings. Therefore, further longitudinal research is needed as an important first step toward understanding mechanistic pathways from socioeconomic status to attainment. Further, Jacob and Parkinson (2015) highlight the importance of longitudinal studies for looking at changes in attainment and executive function over time. Given the substantial concurrent associations between executive function and attainment, studies that look at time 1 executive function as a predictor of time 2 attainment without time 1 attainment and time 2 executive function measures may simply be picking up on executive function-executive function or attainment-attainment associations.

Any further study should employ adequate controls for demographic factors (e.g., ethnicity, first language status) that may confound and lead to overestimation of

socioeconomic status effects on executive function and attainment (e.g., Sirin, 2005; Friso-van den Bos et al., 2013). Studies should also capture sufficient variability in socioeconomic status in their samples, so as not to underestimate the magnitude of socioeconomic status to executive function or attainment associations (see White, 1982; Sirin, 2005; Lawson et al., 2018). Practically, it is very difficult to recruit a socioeconomically diverse sample in relatively small psychological studies which typically have more ready access to middle class families. Small scale studies can additionally lack statistical power to control for demographic factors. Therefore, large scale epidemiological studies which often involve representative samples by design are crucial for understanding social inequalities in executive function and attainment.

These reviews also reveal mixed evidence regarding the selectivity of associations between these three constructs. This is likely to be because, at the group level, scores on different socioeconomic status indicators tend to be up to moderately correlated (e.g., Duncan & Magnuson, 2002). Different executive function and different attainment measures also tend to significantly correlate with one another (e.g., Pureza et al., 2011; Zhang & Peng, 2023). Therefore, just including one measure of executive function or socioeconomic status is likely to result in significant results on attainment but not necessarily because it is picking up on something unique about that variable. To truly being to understand specific pathways, we need to simultaneously model multiple indicators of socioeconomic status, executive function and attainment. Schoon and colleagues (Pensiero & Schoon, 2019; Schoon et al., 2021) have made this same point, arguing for a Multiple Exposure Multiple Outcome (MEMO) approach to studying social inequalities. Szucs and Mammarella (2024) have also recently made a similar argument in the context of understanding early maths development.

Although socioeconomic status indices are moderately correlated at the group level, there are many instances where different aspects of socioeconomic status are far from perfectly aligned for individuals. Farah (2017, pp. 56) provides the following examples:

"An adjunct professor will have more education than a plumber but will make less money. A musician in a world-class orchestra may have less education than an office worker, but will have more professional prestige. A resident building superintendent may have little education, prestige, or pay but may benefit from the safety, convenience, and sense of community in a good neighborhood."

I therefore concur with Mousavi et al. (2022) and others (e.g., Duncan & Magnuson, 2002; Davis-Kean et al., 2021; Schoon et al., 2021) that there is value in studying specific pathways from socioeconomic status to attainment. This type of research helps inform and test mechanistic explanations (such as those put forward by Bond, 1981; Banerjee, 2016; Farah, 2017; Thomas & Coecke, 2023) which can be translated into interventions to prevent school failure in low socioeconomic status adolescents.

A study by Tighe and Davis-Kean (2021) illustrates the implications of this point neatly. They looked at four types of US families: low income + low parental education, high income + high education, low income + high education, and high income + low education in the Early Childhood Longitudinal Study 1998–1999. Of note, children from low-income families but with parents educated to at least college level outperformed children from high income + low education and low income + low education families in maths but not literacy. The former group's parents were also more likely to engage them in educationally enriching activities such as library and museum visits. These findings provide examples as to how families utilise what resources they have to try to provide the best possible outcomes for their children. Such an approach is a move away from the research tradition of lumping all low socioeconomic

status individuals together and expecting similar outcomes. Tighe and Davis-Kean's findings show that the needs of individuals are likely to differ depending on their specific combination of socioeconomic circumstances. They also show that studies using just a single indicator of socioeconomic status are likely to miss out on important nuance.

1.7 What is already known about adolescence?

Presently, only four longitudinal cohort studies have data on executive function during adolescence[5]: the *Avon Longitudinal Study of Parents and Carers* (ALSPAC; https://www.bristol.ac.uk/alspac/), which follows over 10,000 children born in the South West of England in 1991-92 from birth, the NICHD *Study of Early Child Care and Youth Development* (SECCYD; https://www.nichd.nih.gov/research/supported/seccyd), a birth cohort study of just over 1,000 individuals from 10 different sites across the US who were 0-3 years old in 1991-94, the *Growing Up in Australia: The Longitudinal Study of Australian Children* (LSAC) which follows a population representative sample of 5,000 children who were aged 0–1 years in 2003–04 and an additional 5,000 children who were 4–5 years in 2003–04, and the *Study of Cognition, Adolescents and Mobile Phones* (SCAMP; https://scampstudy.org/) which involves a population representative cohort study of 6,905 adolescents from the greater London area who were first assessed at age 12. Studies using data from ALSPAC, SECCYD and LSAC have yielded important insights about socioeconomic status-executive function associations during adolescence and how socioeconomic status and executive function are related to school attainment in this age group.

[5] Two accelerated longitudinal cohort studies – Beatriz Luna's cohort (described in Tervo-Clemmens et al., 2023) and the *National Consortium on Alcohol & Neurodevelopment in Adolescence* (NCANDA; http://www.ncanda.org/) - have measures of executive function during adolescence for a small subset of their participants. Publications using data from these cohorts typically treat children, adolescents, and adults as one group.

Donati et al. (2019) examined longitudinal associations between parental occupation, various executive function measures taken over adolescence and attainment in GCSE maths, English and science in the ALSPAC cohort (*n* = 15,247). Parental occupational prestige was calculated following the Office of Population Census and Surveys averaged over across three time points (pre- the child's birth, when the child was 4 and when they were 8). Executive function measures were taken at 10 years (the Counting Span and Stop Signal tasks; Case et al., 1982; Logan & Cowan, 1984), 11 years (the Sky Search, Dual task, and Opposite Worlds task from the Tests of Everyday Attention for Children; Manly et al., 2001), 13.5 years (the Digit Vigilance, Simple RT and Choice RT tasks from the Cognitive Drug Research computerised cognitive assessment system), 15.5 years (Stop Signal task) and 17 years (N-Back Task; Manly et al., 2001).

They found that parental occupation and a factor of the working memory measures were associated with change in attainment in each subject over adolescence. These effects were small to moderate in size, with larger effects for working memory compared to parent occupation ($\beta_{\text{parental occupation-maths}} = .10$; $\beta_{\text{parental occupation -science}} = .11$; $\beta_{\text{parental occupation-English}} = .13$; $\beta_{\text{working memory-maths}} = .39$; $\beta_{\text{working memory-science}} = .32$; $\beta_{\text{working memory-English}} = .23$). Working memory was a stronger predictor of maths and science attainment at 16 than any earlier attainment measures. Their processing speed factor significantly negatively predicted attainment in English ($\beta = -.05$) and positively predicted attainment in maths ($\beta = .04$), while their inhibition factor was not significantly associated with performance in any GCSE subject. These finding show that some aspects of socioeconomic status and executive function are related to attainment across subjects in adolescence. By controlling for age 11 attainment, Donati et al. (2019) were able to show that these associations were specific to adolescence and not explained by the association between socioeconomic status and attainment during

childhood. This is suggestive of some effects of socioeconomic status on attainment unfolding during secondary education.

Ahmed et al. (2019) looked at longitudinal associations between different aspects of socioeconomic status, different types of executive function and attainment in literacy and maths in the SECCYD sample (n = 1,273). A battery of executive function measures was completed at 54 months measuring delay of gratification (Mischel, 1974), verbal working memory span (Memory for Sentences task; Woodcock & Johnson, 1989); sustained attention (Continuous Performance Task; Rosvold et al., 1956), and inhibition (Children's Stroop task; Gerstadt et al., 1994). At 15 years, an additional battery of tests was completed measuring planning (Tower of London; Berg & Byrd, 2002), working memory (Numbers and Letters task; Turner & Engle, 1989), and inhibition (Stroop Test; Stroop, 1935). Measures of academic attainment were taken at both timepoints using the Woodcock-Johnson Revised Tests of Achievement (Woodcock & Johnson, 1989). At 54 months, literacy was measured by the Picture Vocabulary subscale and by the Verbal Analogies and Passage Comprehension subscales at 15 months. Maths achievement was measured by the Applied Problems subscale at both measurement points. Data on maternal education level at the time of the child's birth and family income to needs ratio calculated when the child was 1-54 months were used as socioeconomic status indices. Socioeconomic status indices were included as predictors in the multiple regression models alongside other sociodemographic measures, attainment and executive function measures at 54 months, and a measure of the home environment.

They found that 54-month attainment in the same subject and maternal education were significantly associated with literacy attainment at 15 years ($\beta_{\text{maternal education}}$ = .16-.18; $\beta_{\text{prior attainment}}$ = .14 - .39) and maths ($\beta_{\text{maternal education}}$ = .17; $\beta_{\text{prior attainment}}$ = .31), but income to needs ratio did not predict performance in either subject. Consistent with Donati et al. (2019), they found that working memory skills were predictive of adolescent attainment, but Ahmed

et al. (2019) observed subject-specific results. More specifically, 54 month working memory predicted adolescent achievement measured by passage comprehension (β = .12). However, unlike in Donati et al., no executive function measures were significant predictors of mid adolescent mathematics attainment. Also, unlike in Donati et al., executive function measures taken during adolescence were not associated with adolescent attainment, no other executive functions were significant predictors of mid adolescent attainment and their socioeconomic status indices did not longitudinally predict any executive function measures.

Several key differences between Donati et al.'s (2019) and Ahmed et al.'s (2019) studies may explain these discrepancies. First, Donati et al. used data from standardised national exams as their outcome measure and Ahmed et al. used measures of specific abilities within maths and literacy. General measures such as national exam performance have been shown to be more strongly predicted by executive function skills than more specific measures (Friso-van den Bos et al., 2013), so this may explain why Ahmed et al. observed much smaller effects of working memory on attainment.

Second, they used different indicators of socioeconomic status so differences between studies in terms of the relationships between socioeconomic status, executive function and attainment may simply reflect different pathways from socioeconomic status to attainment. However, it is surprising that household income was not a good predictor of executive function or attainment in Ahmed et al., whilst parental occupation was in Donati et al. given that the two are correlated and likely to pick up on overlapping sources of variability when the other is not accounted for. This may therefore reflect differences in the reliability of the socioeconomic status measures between the two studies; Donati's average of parental occupation over an 8-9 year period is likely to be more sensitive to change in family socioeconomic status over the primary school years and of family's current socioeconomic circumstances at the time of the study than Ahmed et al.'s singular measure of income to

needs, taken before the age of 5. Alternatively, these differences could be cultural as other research has shown that parental education, occupation and household income all have unique effects of cognitive skills and educational attainment in UK children (Pensiero & Schoon, 2019; Schoon et al., 2021).

Sutin et al. (2022) tested whether internalising and externalising behaviours mediate the longitudinal relationship between socioeconomic status and executive function during adolescence in the LSAC. They created a weighted index of family socioeconomic status based on parent education level, occupation prestige and income when participants were 10-11 years old and calculated a census derived relative neighbourhood deprivation index (the Socio-Economic Indexes for Areas; Pink, 2008). Executive function measures (Identification, One-Back, and Groton Maze Learning) were taken at 14-15 years from the Cogstate (http://www.cogstate.com) battery. Both family and neighbourhood socioeconomic status were associated with performance on the attention measure, whilst family socioeconomic status was uniquely associated with error monitoring (Groton Maze Learning) and neighbourhood socioeconomic status with working memory (One-Back)[6]. Hyperactivity levels mediated the association between family socioeconomic status and adolescent attention and error monitoring and emotional symptoms, and peer problems mediated the family socioeconomic status-attention association.

Together, these results suggest that:

1. Parental occupation (Donati et al., 2019), parental education and household income (Ahmed et al., 2019) are related to educational attainment during adolescence. However, no previous studies have looked at the relationship between neighbourhood deprivation and attainment during adolescence. Moreover, the other three socioeconomic status indicators

[6] Standardised betas were not detailed.

only appeared in one study each with a maximum of one other socioeconomic status indicator included in the same model. Research simultaneously modelling paths from all four aspects of socioeconomic status to attainment is needed to understand pathways from socioeconomic status to educational attainment.

2. Parental occupation (Donati et al., 2019) and neighbourhood deprivation (Sutin et al., 2022), but not parental education and household income (Ahmed et al., 2019), are related to executive function during adolescence. These results are suggestive of specific pathways. However, again these predictors have only been explored in one study each, with no other socioeconomic status indicators modelled simultaneously, so these results need replicating in the manner described above.

3. Individual differences in working memory skills predict adolescent attainment. However, there is mixed evidence about whether adolescent working memory skills, as opposed to working memory skills measured earlier in life, predict attainment.

Although research using these datasets has made valuable contributions to our understanding of the nature of associations between socioeconomic status, executive function and attainment during adolescence, they are not without limitation. The LSAC only has measures of executive function at one timepoint, meaning that it was not possible for Sutin et al. (2022) to study socioeconomic status as a predictor of change in executive function over adolescence. Further, neither SECCYD, nor ALSPAC (with the exception of a single task), have the same measures of executive function at different timepoints, making it difficult to study factors associated with developmental change in executive function skills. In these cohorts, an apparent change in scores over development could be attributed to the different measures tapping a slightly different subset of skills or the developmental appropriateness of the task. To deal with this limitation of the ALSPAC data, Donati et al. (2019) chose to group

the executive function measures taken at different ages using principal component analysis, meaning that they were unable to look at socioeconomic status as a predictor of developmental change in executive function. Ahmed et al. (2019), by contrast, kept the measures taken at different timepoints separate, but found little stability in executive function in their study, with only working memory measures showing a significant longitudinal association across timepoints. This limitation might explain the discrepancies between Ahmed et al. and Donati et al.'s results.

1.8 Aims

The Study of Cognition, Adolescent and Mobile Phones (SCAMP) therefore provides an exciting opportunity to reliably study the relationship between socioeconomic status and the development of executive function skills over adolescence for the first time in a dataset of thousands of pupils. Currently the largest longitudinal dataset of cognitive measures for this age group, it offers an excellent opportunity to study questions about the development of executive function in adolescence. Amongst other measures, data on the same five different executive function tasks at two timepoints during adolescence are available for this cohort. Using data from SCAMP, I was therefore able to test whether any effects of socioeconomic status on executive function occur specifically during adolescence.

The executive function measures in the SCAMP study were specifically selected to be sensitive to developmental changes across the age range studied. Working memory has been shown to have a particularly protracted developmental trajectory, continuing to develop into the mid-20s (Ferguson et al., 2021; Lee et al., 2013). For this reason, most of the executive function measures in SCAMP are working memory measures. Although this limits what can be learnt about relations between other aspects of executive function, socioeconomic status, and attainment from SCAMP, there is more evidence to suggest that these skills show a socioeconomic gradient and might explaining social inequalities in adolescent attainment

than other executive function skills (see Ahmed et al., 2019; Donati et al., 2019; Sutin et al., 2022).

This thesis further set out to test whether the longitudinal effects of socioeconomic status on attainment via executive function seen in previous studies (e.g., Albert et al., 2020; Ng et al., 2021; Waters et al., 2021) replicate when specifically focusing on adolescents and when prior executive function skills and attainment are controlled for. The recent linkage of the SCAMP data with school records from Department for Education's National Pupil Database enabled us to answer, for the first time, whether widening gaps in attainment over adolescence linked to socioeconomic status are linked to (and consistent with a causal effect of) widening gaps in executive function. Research that uses performance on standardised national exams as an outcome measure has clear practical applications (Figlio et al., 2017). Further, general measures of attainment are more sensitive to individual differences in executive function than measures of a specific ability (e.g., maths grade point average versus an arithmetic measure; Friso-van den Bos et al., 2013). I explore additional pros and cons of using administrative data in research in more detail in Bowen et al. (under review).

This thesis also expands on previous research on adolescents (Ahmed et al., 2019; Sutin et al., 2022) to further understanding of different pathways from socioeconomic status to attainment. To do this, we looked at the relationship between a comprehensive range of socioeconomic status indicators (pupil's number of university educated parents, their parents' highest occupation, Free School Meals status – a measure of household poverty, and relative area level deprivation) available for the SCAMP cohort and performance, or change in performance, on a range of different executive function and attainment measures. In addition to having multiple measures of socioeconomic status available for this cohort, a benefit of using SCAMP to understand socioeconomic status to attainment relationships is that participants come from the most socioeconomically diverse region of England: the greater

London area (McRae & Westwater, 2023). The recruitment strategy was also designed to try to sample a population representative group of adolescents. Using SCAMP data, I was therefore able to overcome the sampling range limitations of many previous studies and the cohort represents sufficient variability in socioeconomic status to meaningfully study its relationships with executive function and attainment.

SCAMP participants were 16 years old in 2018-2020, meaning that this dataset is more current than the aforementioned cohort studies. The most comparable cohort, the ALSPAC sample, are now in their early 30s and their experience of growing up in their given socioeconomic circumstances are likely to differ markedly from children born after the millennium growing up in similar socioeconomic circumstances. Factors such as the financial crisis and the massive cuts to youth funding in the UK that occurred since the ALSPAC pupils were adolescents are likely to have impacted on what it means to be an adolescent from a low socioeconomic status family. Therefore, research making use of data on recent adolescents is needed to understand the current links between socioeconomic status, executive function, and attainment in the UK. Provision of a contemporary evidence base gives policymakers a more solid ground to develop policies to address socioeconomic status linked gaps in academic attainment.

1.9 Thesis structure

1.9.1 Chapter 2: General methodology

In the next chapter in this thesis, I describe the SCAMP subsample in more detail, the measures used for the present analyses, the data collection procedure and information on data cleaning and analysis relevant to both studies, including assumptions about linearity and the approach used to deal with missing data.

1.9.2 Chapter 3: Longitudinal associations between socioeconomic status and executive function during adolescence are small and specific

This chapter uses multiple regression and structural equation modelling to test whether socioeconomic status predicts executive function cross-sectionally (at age 11) and change in executive function over adolescence in this cohort and whether these effects are specific to certain socioeconomic status indices or executive function measures. The following research questions are addressed:

1. What is the nature of associations between socioeconomic status and executive function during adolescence?
    a. Are some socioeconomic status indicators better predictors of executive function skills than others?
    b. Are these effects of socioeconomic status on executive function during adolescence indiscriminate, or are some aspects of executive function more related to socioeconomic status?
2. Does the socioeconomic status gradient in executive function skills increase during adolescence?

1.9.3 Chapter 4: The widening socioeconomic status gradient in attainment over adolescence is related to widening gaps in working memory skills

Informed by the findings from the first study, in Chapter 4, I then use structural equation modelling to test whether change in executive function over adolescence mediates the association between socioeconomic status and attainment at 16 (controlling for age 11 attainment). Again, the specificity of these effects is evaluated by comparing a series of increasingly complex models. The following research questions are addressed:

3. Does change in executive function skills over adolescence explain widening social inequalities in attainment?
4. Do executive function skills have bigger effects on attainment in certain subjects during adolescence?
5. Are some aspects of executive function better predictors of attainment than others?
6. Which aspects of socioeconomic status are predictive of widening attainment gaps over adolescence?
    a. Is there any evidence for different pathways from different aspects of socioeconomic status to attainment via working memory?

1.9.4 Chapter 5: Conclusions

The final chapter in this thesis describes the overall conclusions from this body of work in the context of the wider literature. It also deals with the general limitations of the findings presented in this thesis, particularly with respect to how they inform causal accounts, as well as directions for future research.

Chapter 2: General methodology

2.1 About the Study of Cognition, Adolescent and Mobile Phones

The studies presented in this thesis make use of data from the Study of Cognition, Adolescent and Mobile Phones (SCAMP; https://scampstudy.org/). The study is based at Imperial College London and supported by collaborators from University of Cambridge; University College London; University of Edinburgh; Birkbeck, University of London; and Swiss Tropical and Public Health Institute. SCAMP was initially funded by the Department of Health and Social Care (2014-2020) and, since 2021, is funded by the Medical Research Council. It was set up to study the effects of mobile phone use on the teenage brain, at a time when there was significant concern about the effects of exposure to radio waves from mobile phones (e.g., see Cotgreave, 2005).

The SCAMP cohort includes 6,905 participants from 39 schools (26 state; 13 independent schools) from the greater London area and surrounding counties (**Figure 2.1**). Schools were recruited with the aim to achieve a nationally representative sample. For a description of the full cohort please refer to Toledano et al. (2018). Pupils were first assessed when they were 11-12 (T1; November 2014 - July 2016) and again at around 13-15 years (T2; November 2016 - July 2018). Eight schools dropped out of the study after the initial testing session (attrition rate = 24%; $n \sim 1{,}593$ adolescents). Further rounds of data collection have been completed, but I focus only on these two initial testing sessions as the same cognitive measures were employed at these timepoints.

Figure 2.1

Map showing the geographical distribution of participating schools.

REDACTED

Note. Reproduced from https://scampstudy.org/about_scamp/

2.1.1 Linkage with National Pupil Database data

The SCAMP data was recently linked with data from the National Pupil Database to allow us to study the associations of cognitive and sociodemographic factors with school outcomes. Ethical approval for this linkage was granted by the Imperial College London Research Ethics Committee (Protocol number 14IC2067, version 4, 29/07/2014). Parents consented to data linkage at the stage of first enrolling in the study. The participant information booklet which explains the various data linkages undertaken as part of the SCAMP study can be found at https://www.scampstudy.org/wp-content/uploads/2018/11/Parent-information-leaflet.pdf.

The data controller at Imperial College shared participants' full names, dates of birth, postcodes and schools' unique reference numbers with Department for Education in order so that they could identify participants within the National Pupil Database. Identification was achieved through full matching based on these data points through a comprehensive search of all current and historic National Pupil Database records. Following this, fuzzy matching with names, dates of birth and unique pupil numbers was carried out. Department for Education then provided the SCAMP team with a pseudonymised extract of the requested data through secure file transfer.

This approach was taken rather than Department for Education's standard linkage process which operates through Office for National Statistics Secure Research Service. Through the Secure Research Service, data scientists at Office for National Statistics themselves link National Pupil Database data with the research data shared with them. This alternative approach was necessary as consent forms laid out that no further SCAMP data beyond the demographics listed above would be released to third parties. Since the data extract was required for other SCAMP subprojects involving very large amounts of data (including data on air pollution for the whole of London ~ 300gB), it was also not practical to send all the necessary data to the Office for National Statistics for them to carry out the linkage. The appended data sharing agreement (**Chapter 2 Appendices: Appendix A**) was drawn up between Department for Education, Imperial College London and Birkbeck College, stipulating the appropriate procedures for storage and use of the data.[7]

[7] Note that through my Bloomsbury Colleges studentship, I had joint university affiliation between University College London's Institute of Education and Birkbeck College.

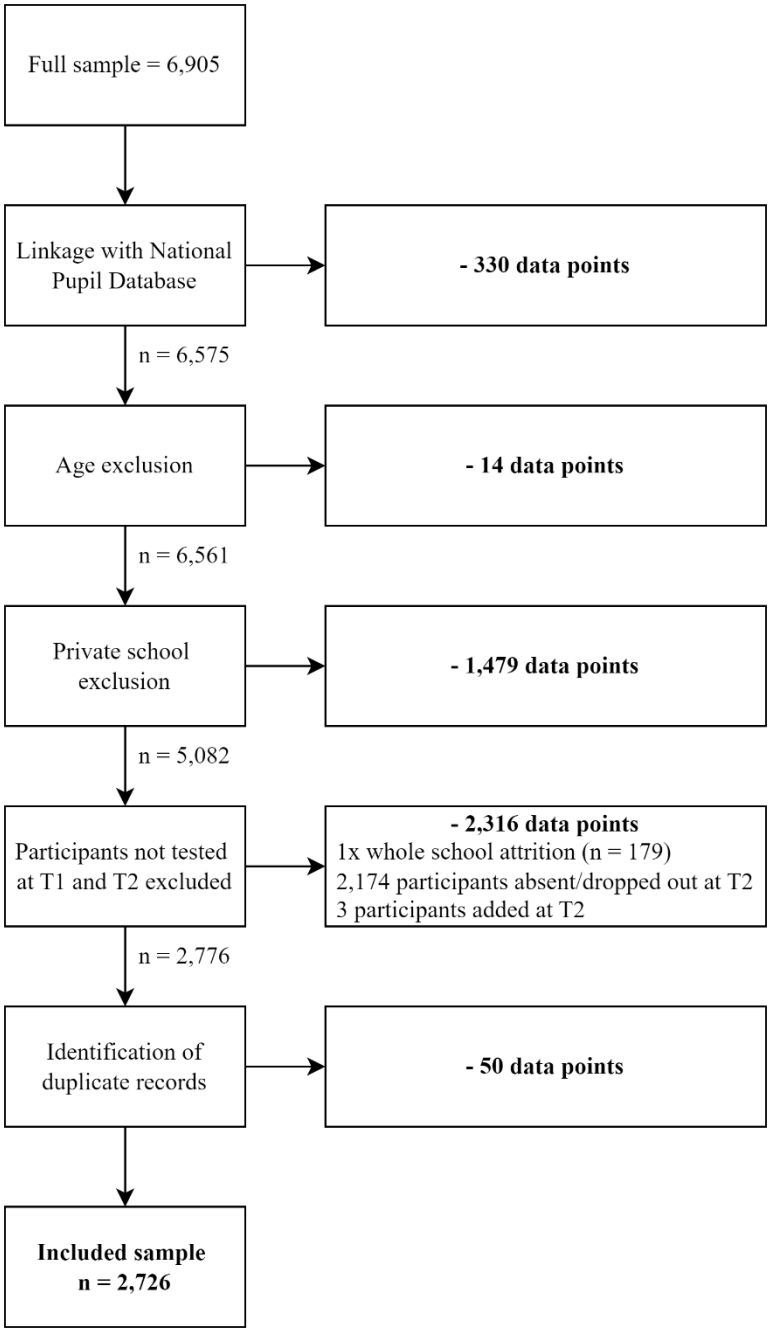
I received the cohort and National Pupil Database data in separate pseudonymised files via secure transfer from the data controller at Imperial College. I was also sent a third file containing both the unique identifiers used in the National Pupil Database and those used in the SCAMP records. I linked the SCAMP and National Pupil Database datasets based on unique identifiers through this third file using base R's inner join function. Data are stored in their original file format on a Birkbeck managed laptop with encryption turned on and not shared beyond my supervisory team.

2.2 Participants

Figure 2.2 gives a flow chart showing how the final analytic subsample was selected. The exclusion criteria are explained in the following sections (**2.21-2.2.2**).

Figure 2.2.

A visual representation of the processes through which I filtered down from the full SCAMP sample (N = 6,905) to the included subsample (n = 2,726).



2.2.1 Data loss from linkage and cleaning

I included participants in the following studies for whom we successfully identified their educational records in the National Pupil Database (the UK Department for Education's administrative database, N = 6,575). I excluded 14 pupils outside of the age limits 10.40–13.51 years at T1 or 13.00-16.00 years at T2.

2.2.2 Selection based on school type

The majority of pupils in England are educated in state schools (Staufenberg, 2022). These are local authority or government funded, and thus free to attend, and teaching follows the National Curriculum. Eligibility for school enrollment is largely determined by the proximity of a pupil's home to the school and it is uncommon for state schools to have selection criteria based on academic ability. All pupils attending state funded secondary schools are required to sit General Certificate of Secondary Education (GCSE) exams in mathematics, English and science at aged 16. A smaller proportion of UK students are privately educated. Private schools are all fee paying (although some scholarships are offered to gifted students from deprived backgrounds) and many select based on academic ability. These schools may opt for alternative curriculums, rather than the National Curriculum, and it is common for different forms of standardised assessment to be taken.

Due to self-selection, the SCAMP cohort has an overrepresentation of privately educated pupils relative to the national average, with 21% of pupils enrolled in private schools compared to only 6% of pupils in England (Green, 2022). More than 90% of privately educated pupils in SCAMP did not sit GCSEs in the three core subjects and many also did not have SAT results available, presumably because they also attended private primary schools. I thus decided to exclude all private school pupils (n = 1,479 after age exclusion) as most were missing the key outcome measures and key predictors used in the following studies. My decision not to include privately educated pupils who did have GCSE

and/or SAT results was motivated by a desire to have a relatively homogenous sample in terms of the education system they have been exposed to. This is because SCAMP has few to no measures of classroom environment, teaching, etc. through which to control for these effects on attainment and cognitive development.

2.2.3 Included participants

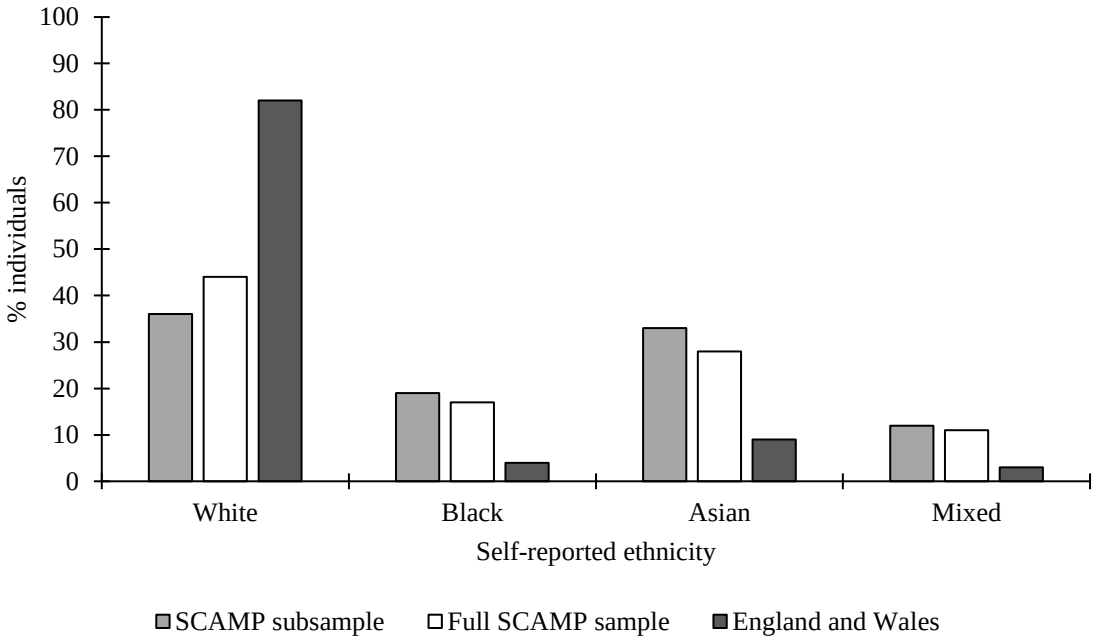
Since there was 24% attrition at T2, I focused my analyses on pupils who were present for both testing sessions. I identified that gender was the variable with the highest *n*, so filtered for participants with gender information at T1 and T2. This resulted in a final *n* of up to 2,726 (54% female). The exact sample size varies per measure as demographic questions were optional self-reports and because participants only had the length of one lesson to complete the test battery so later measures have higher rates of missingness (for further detail on this please see section **2.5.1**). These participants form the sample for both studies presented in this thesis.

Participants were in Year 7 when they were first assessed (M = 12.06 years, SD = 0.38) and then in Year 9/10 (M = 14.29, SD = 0.48) at the second assessment. Please see **Figure 2.3** for comparisons of the sociodemographic composition of this sample, relative to the figures for the UK as a whole. As SCAMP is an epidemiological study, it is important that the sample is representative and matches the sociodemographic distribution of England, with matching usually assessed on metrics such as ethnicity, first language status, and socioeconomic status. **Table 2.1** gives the actual figures for the whole SCAMP cohort and the studied subsample. Please refer to Toledano et al. (2018) for further details on the whole cohort.

Figure 2.3

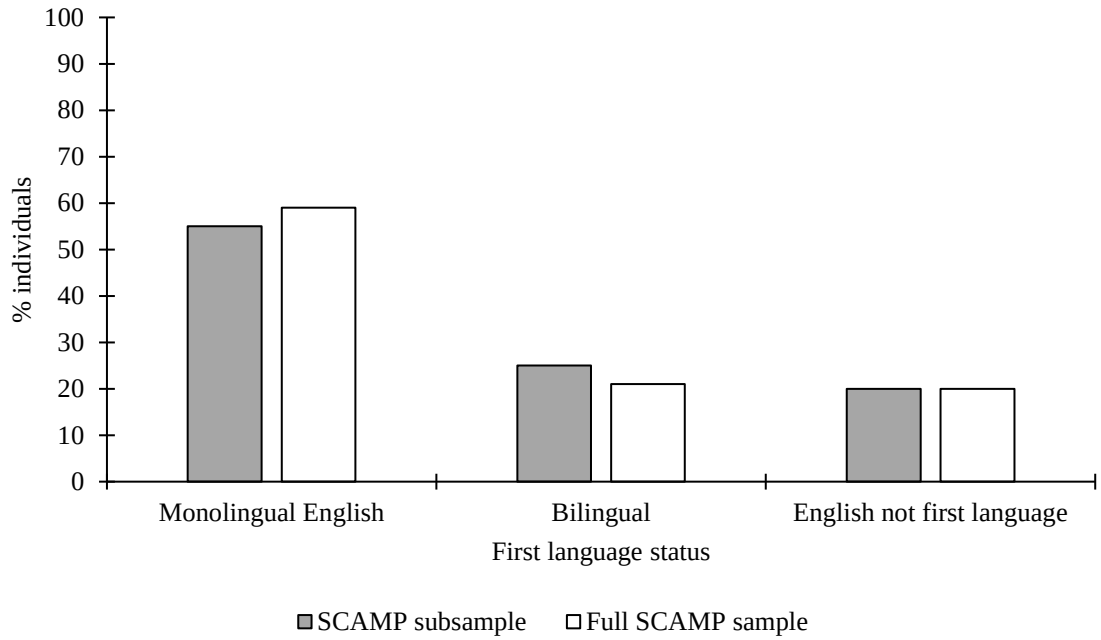
Bar graphs showing the sociodemographic distribution of the SCAMP subsample across the indices of **a.** ethnicity, **b.** first language status, **c.** parent education level, **d.** parental occupation, **e.** area level deprivation, and **f.** free school meals status. **Figures a** and **d-f** compare the figures for the subsample to England as a whole. All percentages are expressed as a total of the individuals who provided data for that measure.

a.

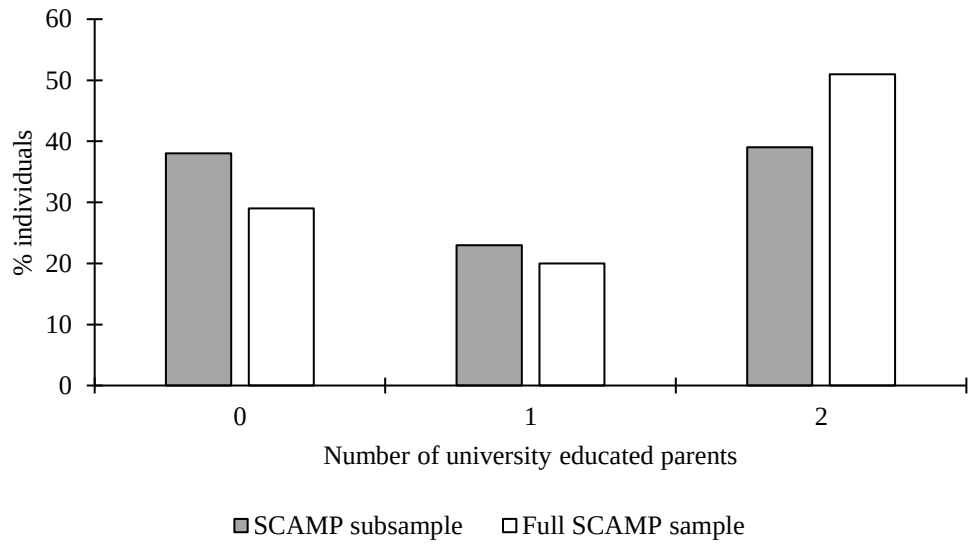


Note. Figures are from the 2021 Census for England and Wales (GOV.UK, 2022).

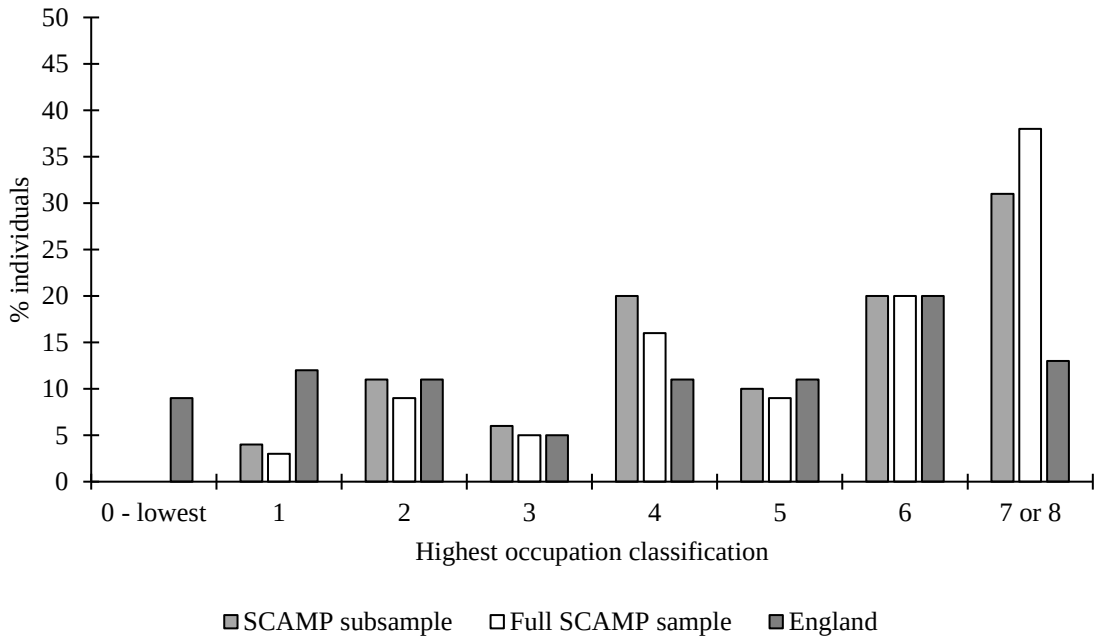
b.


100
90
80
70
60
50
40
30
20
10
0
% individuals
Monolingual English
Bilingual
English not first language
First language status
SCAMP subsample
Full SCAMP sample

c.

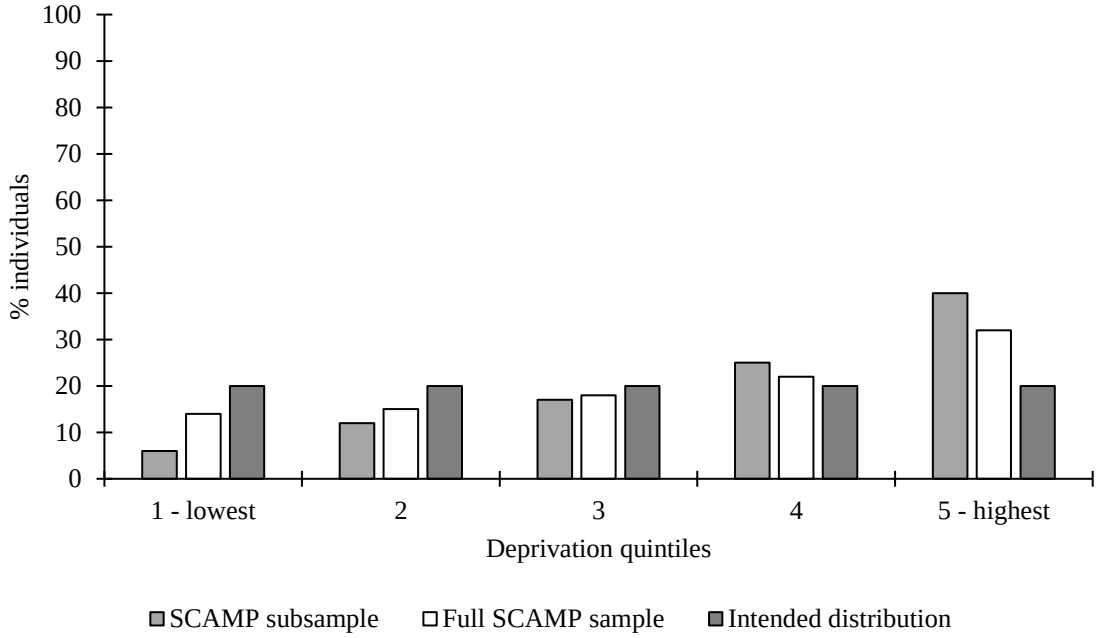

60
50
40
30
20
10
0
% individuals
0
1
2
Number of university educated parents
SCAMP subsample
Full SCAMP sample

d.



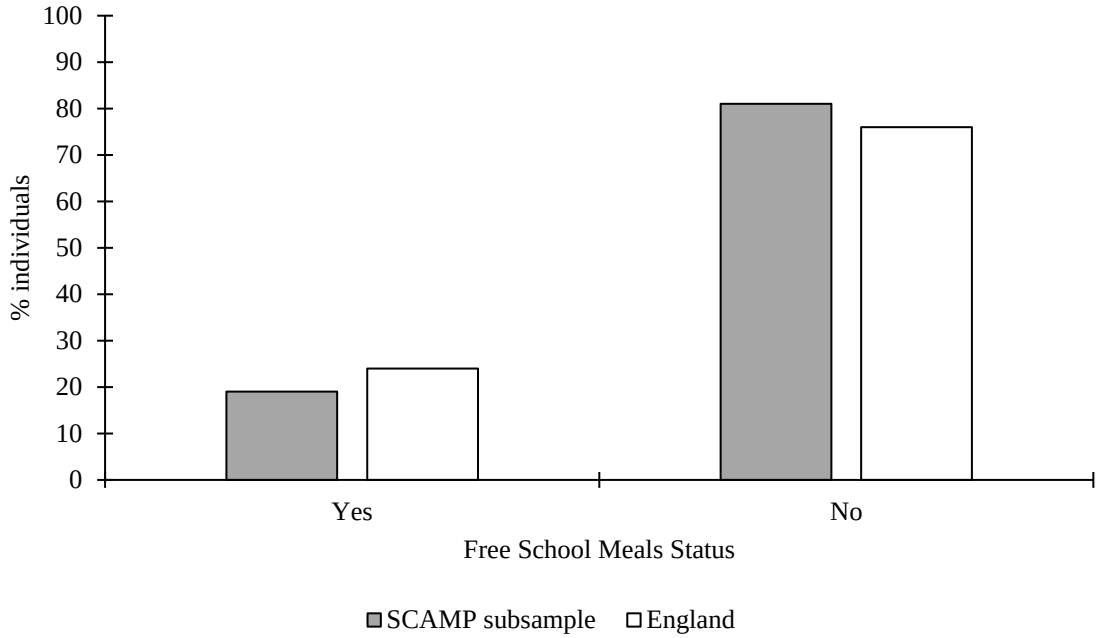
N.B. Parental occupation rankings follow the Office for National Statistics classification system (Office for National Statistics, 2010). Figures for England are from 2021 Census data on all adults aged over 16 (Office for National Statistics, 2022). Note that the data on the English adult population collapsed categories 7 and 8. I grouped these here to aid comparison, but these are treated as separate categories in my analyses.

e.



N.B. The intended distribution is 20% in each category as the index divides the country into quintiles.

f.



N.B. Figures for England are from state school pupils in the 2022/23 academic year (GOV.UK, 2023b).

Table 2.1

Sociodemographic characteristics of the subsample included in the present study compared to the full sample present at T1 testing who were identified in the National Pupil Database.

	Subsample	**Full SCAMP cohort**
	M (SD)	***M (SD)***
T1 Age	12.06 (0.38)	12.05 (0.41)
T2 Age	14.29 (0.48)	14.25 (0.47)
	N (%)	***n (%)***
Self-reported gender	**2,726**	**6,561**
Female	1,482 (54%)	3,442 (52%)
Male	1,244 (46%)	3,112 (48%)
First language	**2,713**	**6,526**
English	1,483 (55%)	3,865 (59%)
English learnt at the same time as another language	674 (25%)	1,384 (21%)
Not English	556 (20%)	1,277 (20%)
Ethnicity	**2,513**	**6,015**
White (British, Irish, other)	904 (36%)	2,658 (44%)
Black (Caribbean, African, other)	477 (19%)	1,009 (17%)

Asian (Indian, Pakistani, Bangladeshi, Chinese, other)	822 (33%)	1,667 (28%)
Any mixed race	310 (12%)	681 (11%)
Number of parents who attended university (T2)	**1,934**	**4,304**
0	730 (38%)	1,237 (29%)
1	443 (23%)	853 (20%)
2	761(39%)	2,214 (51%)
Parental highest occupation† at T1	**2,335**	**5,611**
Never worked/long term unemployed	0 (0%)	0 (0%)
Routine	91 (4%)	191 (3%)
Semi-routine	248 (11%)	497 (9%)
Lower supervisory and technical	146 (6%)	272 (5%)
Small employers and own account workers	456 (20%)	908 (16%)
Intermediate	227 (10%)	482 (9%)
Lower managerial, administrative and professional	459 (20%)	1,119 (20%)
Higher professional	555 (24%)	1,525 (27%)
Large employers, higher managerial and administrative	153 (7%)	617 (11%)
Deprivation index at T1	**2,651**	**6,375**
1 – least deprived	156 (6%)	916 (14%)
2	330 (12%)	939 (15%)
3	442 (17%)	1,118 (18%)
4	664 (25%)	1,385 (22%)
5 – most deprived	1059 (40%)	2,017 (32%)
In receipt of Free School Meals in Year 7	**2,617**	**4,891**
Yes	493 (19%)	1,000 (20%)
No	2,124 (81%)	3,891 (80%)

†Parental occupation rankings were based on the Office for National Statistics classifications (Office for National Statistics, 2010). Percentages are expressed as a proportion of the total number of participants with data on that measure.

Compared to national figures, the sample included in the analyses was more ethnically diverse and had a higher rate of non-monolingual English speakers (as per 2011 Census records, 90% of people in England and Wales are monolingual English or bilingual from birth; GOV.UK, 2018b). The sample participants were also more frequently from areas with greater levels of deprivation and involved a comparable proportion of free school meal recipients to the national figures (GOV.UK, 2023b). By contrast, the subsample reflected a higher proportion of pupils with parents who had attended university (according to 2021

Census estimates, 34% of the English population over 16 are university educated; Office for National Statistics, 2023) and a skew towards higher occupations (note I took the highest occupation of the two parents). This reflects, in part, differences between the Greater London area and England as a whole.

Compared to the full SCAMP cohort (**Table 2.1**), the subsample also reflects slightly greater diversity in first language status and ethnicity and a slightly better and more representative spread in terms of parental education and occupation. Free school meals status was not affected, likely because Free School Meals status is not recorded for private school pupils. However, the distribution of relative area deprivation was less representative in the subsample compared to the total sample since the quintiles were calculated for the whole sample.

2.3 Measures

Cognitive tasks and questionnaires were designed and completed through Psytools software (Delosis Ltd; https://www.delosis.com/psytools/) on school computers. Tasks which are generally administered as pen and paper measures were adapted to be run on computers. In addition to the tasks described here, three other cognitive tasks (dot enumeration, mental rotation and speech in noise) and a series of questionnaires were administered (see Toledano et al., 2018 for details). Data on Free School Meals status and attainment were obtained from the UK Department for Education's National Pupil Database.

2.3.1 Socioeconomic status indices

Number of parents who attended university. Participants were asked *Did your mother attend university?* and *Did your father attend university?* These variables were found to have very high rates of missingness at T1 (34-44%). I noted that this rate dropped by 6% for each parent at T2 and that there was very high consistency between the answers given at both time points (84% for mothers and 85% for fathers). I assumed the T2 reports to be more

accurate, as pupils were older, and so used T2 values instead of T1 values, except in cases where there was a response given at T1 but not T2, when the T1 response was kept.

In the SCAMP subsample, it was much more common to have 0 or 2 university educated parents as opposed to 1 (see **Figure 2.2c**), likely due to assortative mating (e.g., see Robinson et al., 2017). I therefore created a total number of parents who attended university variable (0, 1 or 2). This helped to avoid multicollinearity issues as well as reduce missing data from single parent families. Research has shown that parental highest level of education predicts education promoting beliefs and behaviours in the home environment, irrespective of which parent is more highly educated (Davis-Kean, 2005). However, in this case, I did not adopt the popular dominance approach (which would here look like *at least one parent educated to university level - yes/no*) because this has been shown to underestimate the effect of parental education on child educational attainment when parents are educated to similar levels (Ballarino et al., 2021).

Parental highest occupation. Pupils reported on the occupation of their mother and father using free text responses. This information was translated into an occupational prestige ranking for each of the pupil's parents, with possible ratings from 0 to 8 (where 0 = Never worked/long term unemployed, 1 = Routine, 2 = Semi-routine, 3 = Lower supervisory and technical, 4 = Small employers and own account workers, 5 = Intermediate, 6 = Lower managerial, administrative and professional, 7 = Higher professional, 8 = Large employers, higher managerial and administrative) based on the Office for National Statistics (2010) classification system. For this index, I adopted the dominance approach and took whichever parent had the highest occupation prestige as the rating for their child. This decision was based on the assumption that, like parental education, which parent has the highest occupational prestige has minimal relevance to child outcomes.

Area-level deprivation. Relative area-level deprivation was calculated by the SCAMP team according to the Carstairs's Index (Carstairs & Morris, 1990) using pupils' postcodes. The index uses census data to calculate an area's relative deprivation level on a scale of 1 to 5 (quintile 1 being least deprived). It considers the proportion of male unemployment, lack of car ownership, overcrowding, and head of households in low occupational classes in an area. Estimates were based on 2011 census data.

Free school meals status. This binary (yes/no) measure was used as a measure of household poverty. Pupils with English nationality aged 5-16 are eligible to receive free school meals if they come from very low-income families. Since 2010, the threshold below which families are eligible to claim has been capped at £16,190 per household per annum (pre-tax) for families in receipt of Child Tax Credits. There are also some special categories of pupils that come from families with no recourse for public funding who are eligible, for example the children of parents on work or student visas and asylum seekers receiving support under Part VI of the Immigration and Asylum Act 1999.

The upper threshold for claiming Free School Meals is currently equivalent to less than one adult full-time minimum wage in England (GOV.UK, 2024). Pupils eligible for Free School Meals thus tend to be those living in the most extreme income poverty (Taylor, 2018), with a third of pupils living below the poverty line but whose parents earn above the threshold, ineligible for Free School Meals (Child Poverty Action Group, 2022). This also means that around half of pupils eligible for Free School Meals are from single parent families (Ilie et al., 2017).

2.3.2 Executive function measures

Trail-Making Task. The Trail-Making Task (TMT; Tombaugh, 2004) measured cognitive flexibility. The task involved three dot-to-dot conditions completed in a fixed order, each including 20 dots. Participants had 20 s to make a response, then a warning was

displayed informing them that the task would be abandoned if no response was made in the following 10 s. In the dots condition, participants had to click each individual dot when they turned blue (Figure **2.4a**, top). In the letters condition, dots were labelled with letters and participants had to click them in alphabetical order. In the switching condition, each dot was labelled with a number, or a letter and participants were required to click these in alternating alphabetical and numerical order (**Figure 2.4a**, bottom). This condition assesses flexibility as participants are required to switch between letters and numbers, holding the sequence for each in mind. Before each condition started, a short video demonstration played, then participants completed six practice trials. If an incorrect location was clicked, the instructions were repeated. If an incorrect click was made at the start of the main test, text feedback highlighting the correct starting point was given. Incorrect responses made later elicited an aversive sound. The measure of task performance was the residual from a regression with time to complete the letters condition as the predictor and time to complete the numbers/letters condition as the dependent variable. This measure reflects relative response time on the switching block compared to the single sequence block. Participants with a higher value are those whose were most slowed down by the need to switch between letter and number sequences. Participants who clicked more than 20 times elsewhere than on the dots in any condition were excluded from the analyses.

Backwards Digit Span (BDS). Verbal working memory was measured with the Backwards Digit Span task (Dumontheil & Klingberg, 2012). Single digit numbers were presented visually individually, in sequence, for 1 s, with 1 s separating the numbers. Participants were required to reproduce this sequence in reverse order by selecting numbers on a numerical response pad displayed on screen (**Figure 2.4b**). Participants needed to correctly reproduce two sequences of two digits and one sequence of three digits to proceed to the main task. If they failed to do so after three attempts the task was terminated. In the

main task, sequence length (corresponding to working memory load) could vary between 2 and 9 and was increased or decreased incrementally following the staircase/Levitt procedure (Levitt, 1971). The first trial had a sequence of three items. If the participant responded correctly on this trial, the sequence was increased by three items, then by two after another passed trial, and then by one item for any further successive correct trials. If an error was made the next trial sequence was two items shorter, then decreased by one after any further failed trials, until another passed trial when the staircase would invert. However, failing three trials of the length two at any time resulted in the task being terminated. If participants did not respond after 3000 ms, a "don't know" button appeared. The measure on this task was the average of the mean sequence length of trials with a correct response and the mean sequence length of trials with an incorrect response. Participants who failed the practice or failed all trials of the test phase were not included in the analyses.

Spatial Working Memory (SWM). The Spatial Working Memory Task was used to measure spatial working memory and planning and was adapted from the Cambridge Neuropsychological Testing Automated Battery (Luciana & Nelson, 2002) task of the same name. The task required participants to click on ringing telephones to answer them. Phones were positioned in a pseudo-randomised fashion across the display, and each would ring once per level. Participants had to work out which phone was ringing at a given time and answer that phone, while recalling which ones had already rung to avoid selecting the same phone twice (**Figure 2.4c**). The four levels played out in ascending order of difficulty (4, 6, 8, then 10 items) and constituted a block of trials. Feedback was provided throughout, as was a counter to chart progress through each level. A level was completed when all the phones in the display had been answered. Participants failed a trial if they made twice as many errors as items in the array (e.g., 12 errors on a trial with 6 phones). A trial was also failed if the participant returned to all former active phones from previous trials in that block. If all trials

in a block were failed, the task would stop. Two measures were used. The total number of errors combines within search (picking a phone that had already been picked during this trial) and between search errors (picking a phone that had already been found to ring in a previous trial at this level). The strategy score reflects planning and is the number of excess switches of the starting location on each search at levels 6, 8 and 10; this was based on the assumption that starting the search in the same location on each trial (except if this phone had already rung) would aid performance and reflect planning. Hence, a higher strategy score reflects a less efficient strategy. Participants who did not reach level 10 (n = 24 out of the full sample) were excluded from the analyses.

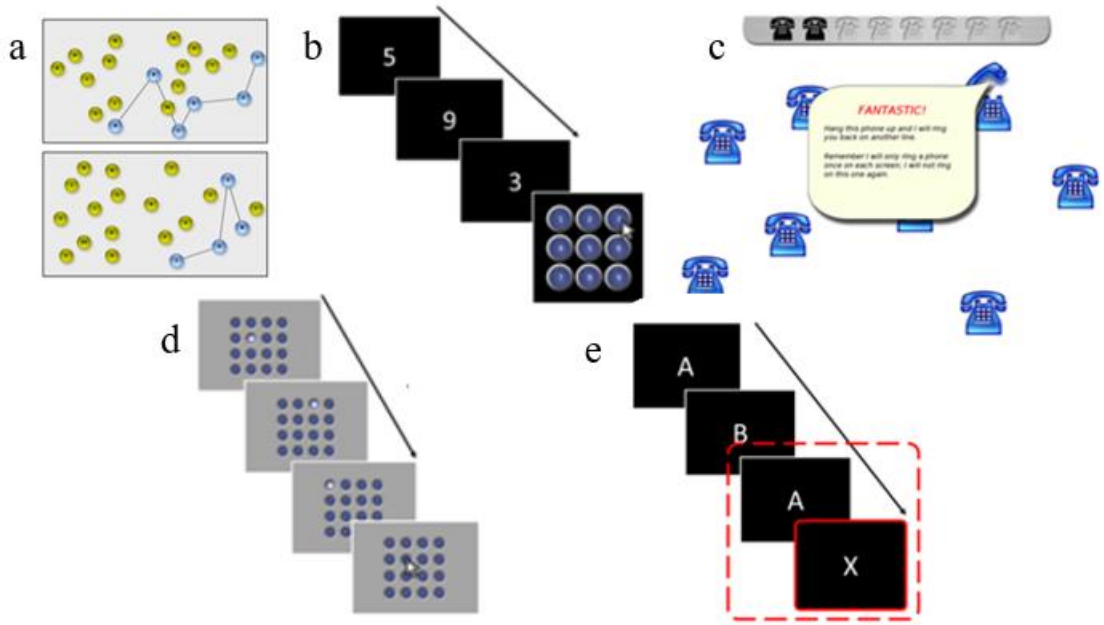
Corsi Block Tapping Task. An additional measure of visuo-spatial working memory was a computerised version of the Corsi task (Corsi, 1972), similar to the tasks used by Alloway (2007) and Dumontheil and Klingberg (2012). Participants saw a 4 x 4 grid of 16 circles which lit up individually (for 600 ms each with 300 ms intervals) in a pseudo-randomised sequence. They had to remember and then reproduce the sequence by clicking the circles in the same order in an empty array (**Figure 2.4d**). Participants were given 3 s to give a response, then a "don't know" button appeared. Any errors terminated the trial and caused a red X to be displayed on the screen. Participants had five attempts to reproduce a correct sequence of three circles in the practice phase. For the main task, the minimum sequence length was 3 circles, and the maximum was 9, with the length of subsequent trials determined by performance on preceding trials. The number of dots was increased or decreased incrementally, in a staircase fashion following the Levitt procedure (Levitt, 1971), in the same way as the BDS task and the measure was calculated in the same way.

AX-Continuous Performance Task (CPT). An adapted form of Brocki and Bohlin's (2004) AX-Continuous Performance Task was used as a measure of sustained attention/distractibility. On each trial, the letters "A", "B", "C", "D", and "X" were presented

for 460 ms followed by a central fixation cross for between 2550 and 2784 ms, during which time participants had to respond with a key press if an X followed an A (**Figure 2.4e**). The task began with an 18-trial practice block with three targets. All three targets had to be responded to correctly, with no more than one commission error. After three failed practice attempts the task was terminated. The test phase comprised 54 trials, with 10 targets. A range of different error types can be considered on this task (Halperin et al., 1991). Here, as the number of trials and the number of errors were low, the key measure was the total number of errors, i.e., the sum of omission errors (not pressing when an X followed an A) and the number of commission errors (pressing for a sequence other than A–X), which reflects inattention, impulsivity, and disinhibition.

Figure 2.4

Cognitive tasks stimuli. (a) Trail Making Task letters (top) and switching conditions (bottom). (b) Example of a Backwards Digit Span task trial. (c) Example of a screen capture from the SWM task showing feedback given for a correct selection. (d) Example of a Corsi Span task trial. (e) Example stimuli from the AX-Continuous Performance Task; participants had to press a key when an X followed an A (highlighted in red).



2.3.3 Educational attainment measures

Key stage 2 Standardised Assessment Tests (KS2 SATs)

All typically developing English pupils educated in state funded primary schools sit SATs in the summer of their final year of primary school (Year 6; age 11). Pupils identified as having special educational needs or social, emotional, and mental health needs can, however, be disapplied. SCAMP pupils sat SATs in reading and maths at this time. Because of the age of the SCAMP cohort, their SATs were graded following the old system where the standard exams captured grades 3 through 5 (4 being the average and the expected standard,

where a higher number reflects a higher grade). At the time the SCAMP participants took their SATs, they could also be entered for level 6 papers. Please see **Table 2.2** and **Chapter 2 Appendices: Appendix B** for overviews of the curriculum and assessment focuses in reading and maths.

Table 2.2

SAT reading assessment focuses. Reproduced with permission from Standards and Testing Agency (2013).

Assessment focus	Criteria
1	use a range of strategies, including accurate decoding of text, to read for meaning
2	understand, describe, select or retrieve information, events or ideas from texts and use quotation and reference to text
3	deduce, infer or interpret information, events or ideas from texts
4	identify and comment on the structure and organisation of texts, including grammatical and presentational features at text level
5	explain and comment on writers' uses of language, including grammatical and literary features at word and sentence level
6	identify and comment on writers' purposes and viewpoints, and the overall effect of the text on the reader
7	relate texts to their social, cultural and historical contexts and literary traditions.

Key stage 2 Teacher Assessed subjects

Since 2013, Department for Education have also collected teacher assessed grades for writing and science. These are graded on a scale of 2-6 (6 being the highest possible grade). A subset of teacher assessed marks are externally moderated. Please see **Table 2.3** and **Chapter 2 Appendices: Appendix C** for overviews of the curriculum and assessment focuses.

Table 2.3

Teacher assessed writing assessment focuses. Reproduced with permission from Standards and Testing Agency (2013).

Strand	Criteria
Sentence structure and punctuation	● Vary sentences for clarity, purpose and effect. ● Write with technical accuracy of syntax and punctuation in phrases, clauses and sentences.
Text structure and organisation	● Organise and present whole texts effectively. ● Sequence and structure information, ideas and events. ● Construct paragraphs and use cohesion within and between paragraphs.
Composition and effect	● Write imaginative, interesting and thoughtful texts. ● Produce texts which are appropriate to task, reader and purpose.

General Certificate of Secondary Education (GCSE) exams

All English pupils sit GCSE examinations in English language, maths and science at the end of their final year of compulsory secondary education (year 11; age 16), hence our choice of these subjects as outcome measures. I also focused on performance in these subjects for comparability with previous studies (e.g., Ahmed et al., 2019; Albert et al., 2020; Donati et al., 2019) and because a pass in these subjects is required to access many further and higher education courses, as well as certain occupations (e.g., teaching, medical and engineering professions; Gardner, 2023).

GCSEs are graded on a scale of 1-9 (9 being the highest grade possible, equivalent to an A* in the old grading system), where a grade of 4 (old grade C) is the pass mark. Students may sit foundation or higher papers, depending on their predicted grades; foundation papers are less academically challenging and cover the grades 1-5, whilst higher papers cover grades 3-9. Grades are calculated as a weighted average of pupils' performance across the different papers for that subject and the grade boundaries are dependent on the distribution of performance for pupils in that year group.

English language. The GCSE English language curriculum (see Department for Education, 2013a) aims to provide pupils with the reading and comprehension skills to read fluently and engage critically with a wide range of texts and to use these experiences to improve their own writing. It is designed to support pupils in developing a wide vocabulary as well as knowledge and understanding of grammatical terminology and linguistic conventions for oral and written language. It also assesses the ability to use Standard English appropriately and to write effectively and coherently with correct grammar, punctuation, and spelling. Teaching covers understanding and effective use of spoken language, but this does not form part of the final assessment. Fifty percent of the assessment grade is based on assessment of reading comprehension and 50% on writing.

The first assessment criterion for reading covers the identification and interpretation of implicit and explicit ideas in text and the selection and synthesis of evidence. The second assesses pupils' ability to explain the effect of writers' use of different linguistic and structural techniques using relevant subject terminology. The third criterion looks at how well pupils can compare ideas and perspectives conveyed by different texts and the methods used to convey them and the final reading criterion assesses pupils' critical evaluation skills.

The writing component tests pupils' skills in writing clearly, effectively and imaginatively and in using an appropriate tone, style and register for different forms of writing, purposes and intended audiences. Pupils are also assessed on their ability to organise information appropriately through use of intentional structural and grammatical choices. The range of their vocabulary, their accuracy in spelling, punctuation and grammar and their use of varied sentence structures are additionally examined.

Maths.

The GCSE maths curriculum (see Department for Education, 2013b) is designed to give pupils an understanding of key mathematical methods and concepts and the ability to select and apply these methods appropriately to solve novel problems. It also aims to equip pupils with skills in mathematical reasoning, deduction and inference and the ability to communicate mathematical information in a contextually appropriate manner.

Teaching and assessments are focused on 6 themes. The first theme, *Number*, covers the sequencing of number, numerical operators, and calculation as well as fractions, decimals, percentages, units of measurement and the concept of numerical accuracy. The *Algebra* theme focuses on algebraic notation and vocabulary, rearranging and solving equations and inequalities, graphing linear equations, and interpreting graphs of linear models. The third theme addresses *Ratio, proportion and rates of change* (this involves changing between different units of measurement and using compound units; relations between fractions, decimals and percentages; comparing length, area and volume; and using and understanding equations describing proportions; and using and understanding rates of change graphs and equations), the fourth *Geometry and measures* (covering the property and construction of shapes, units of measurement, measuring lines and angles, Pythagoras' theorem, and vectors), the fifth *Probability* (which assess pupils' understanding of randomness, fairness and equally likely events, sample size considerations and their ability to use and interpret probability diagrams and tables) and the sixth, *Statistics* (which covers sampling and distribution, appropriate use of graphs and tables and descriptive statistics).

The greatest weight is given to use and application of mathematical methods in both foundation and higher papers (40% higher; 50% foundation). This assessment criterion tests pupils' ability to recall facts accurately and carry out multi-step tasks, as well as their use and understanding of terminology, definitions, and mathematical notation. Assessment criteria 2 - reasoning, interpretation, and communication - and 3 - solving problems with mathematics -

are given equal weighting (30% higher; 25% foundation). Criterion 2 assesses pupils' skills in deduction, reasoning, inference, critical evaluation, and interpretation and their ability to accurately communicate findings, arguments, and proofs. Criterion 3 looks at pupils' skills in the translation of problems into (a) mathematical process(es) and the interpretation of results in the context of the problem. It further assesses their ability to understand connections between different aspects of maths and critical evaluation of methods and solutions/results in relation to underlying assumptions.

Science.

The GCSE science curriculum (Department for Education, 2015) aims to grow pupils' scientific and conceptual understanding in the disciplines of biology, chemistry and physics. Specifically, it is hoped that it supports pupils in developing their understanding of methods and processes (and the scientific method more broadly) through undertaking scientific enquiries about real world questions. Pupils are expected to learn and apply skills of observation, modelling, enquiry and problem solving and practical skills. There is also a focus on critical evaluation of evidence-based claims using quantitative and qualitative methods.

Four aspects of working scientifically are taught and assessed: *Development of scientific thinking; Experimental skills and strategies; Analysis and Evaluation;* and *Scientific vocabulary, quantities, units, symbols and nomenclature.* The first theme explores the development of scientific methods and theories, using models for prediction and explanation, limitations of scientific research, ethical issues and the importance of peer review and scientific communication in scientific and applied contexts. The second theme is focused on hypothesis testing, evaluation of methodological appropriateness and safety, recording data with a range of measures and sampling. The third theme gives pupils

experience in and an understanding of how to analyse, present and objectively communicate results. The final theme tests pupils' ability to use scientific vocabulary and units of measurement (including interconversion of units) appropriately as well as their understanding of definitions, quantities and orders of magnitude. For details of discipline specific content assessed, please see Department for Education (2015).

Some pupils projected to attain the highest grades will take triple science. These pupils are awarded separate GCSE qualifications in biology, chemistry and physics. Other high achieving students will sit the higher double science papers, whilst other students will sit foundation double science or single science. Double (otherwise known as combined) and single science pupils still study content from all three scientific disciplines but cover 1/3 less and 2/3 less content, respectively. Combined science pupils therefore receive two science GCSEs and single science pupils receive just one. For the purpose of this thesis, I use the highest grade achieved in a GCSE science qualification for each student.

2.3.4 Control variables

Demographics

Through Psytools, data was collected on participants' age in days at the time of testing and then transformed into their age in years.months. They self-reported on their gender identity (male / female / other); the other gender category was omitted due to too few data points. Participants were also asked whether English was their first language, English was not their first language, or whether they learnt English at the same time as another language. These categories are henceforth referred to as monolingual English, English not first language and bilingual from birth respectively. Participants also indicated which ethnic group they belonged to: English, Welsh, Scottish, Northern Irish, or British / Irish / Gypsy or Irish Traveler / any other White background / White and Black Caribbean / White and Black

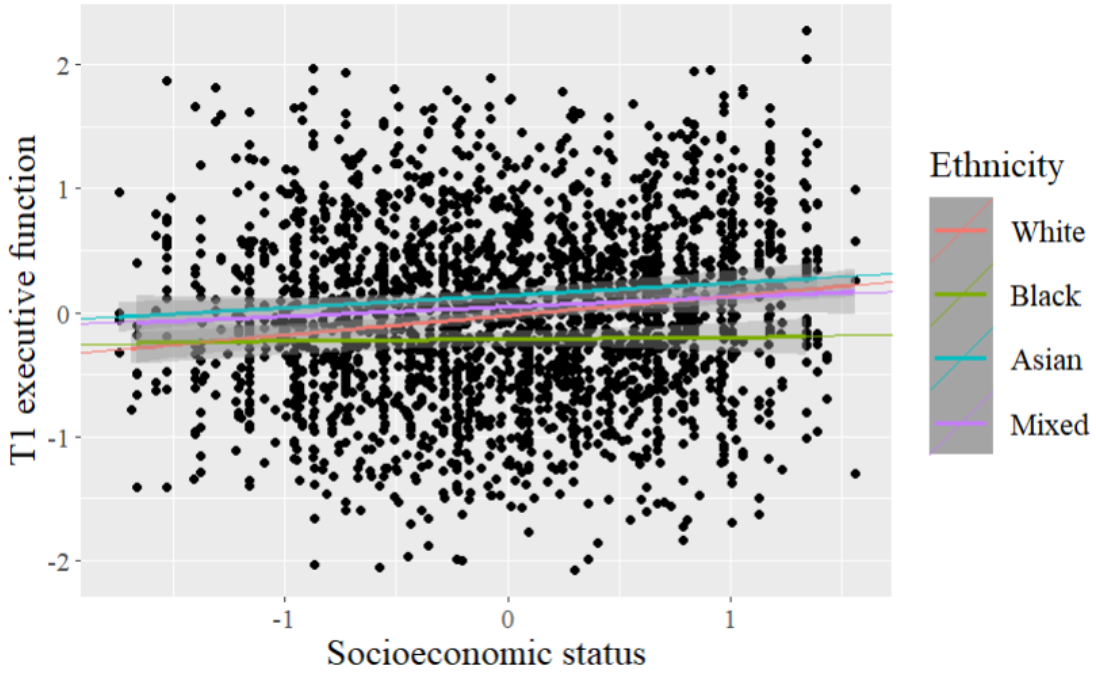
African / White and Asian / any other Mixed or Multiple ethnic background / Indian / Pakistani / Bangladeshi / Chinese / any other Asian background / African / Caribbean / any other Black, African or Caribbean background / Arab / any other ethnic group. From these options, responses were collapsed into five categories - white / black / Asian / mixed / other – and the first four were included as controls. The other option was omitted due to too few data points. I use T1 measures as control variables in all cases.

Davis-Kean and Sexton (2009) showed that ethnicity moderates the association between family characteristics and attainment, but I found little evidence to suggest that this was true for the socioeconomic status to attainment relationship in this sample (see **Figure 2.5**) or for the socioeconomic status to executive function association (**Figure 2.6**). Positive associations between socioeconomic status and executive function and socioeconomic status and attainment were seen in all ethnicity groups although these were attenuated in groups representing lower diversity in socioeconomic status (**Figure 2.7**). I therefore decided not to split the data by ethnic group in any analysis but included ethnicity as a predictor to maximise statistical power.

Figure 2.5

Scatterplots showing the associations between socioeconomic status and **a.** T1 executive function and **b. T2** executive function (all factor scores) within different ethnicity groups.

a.



b.

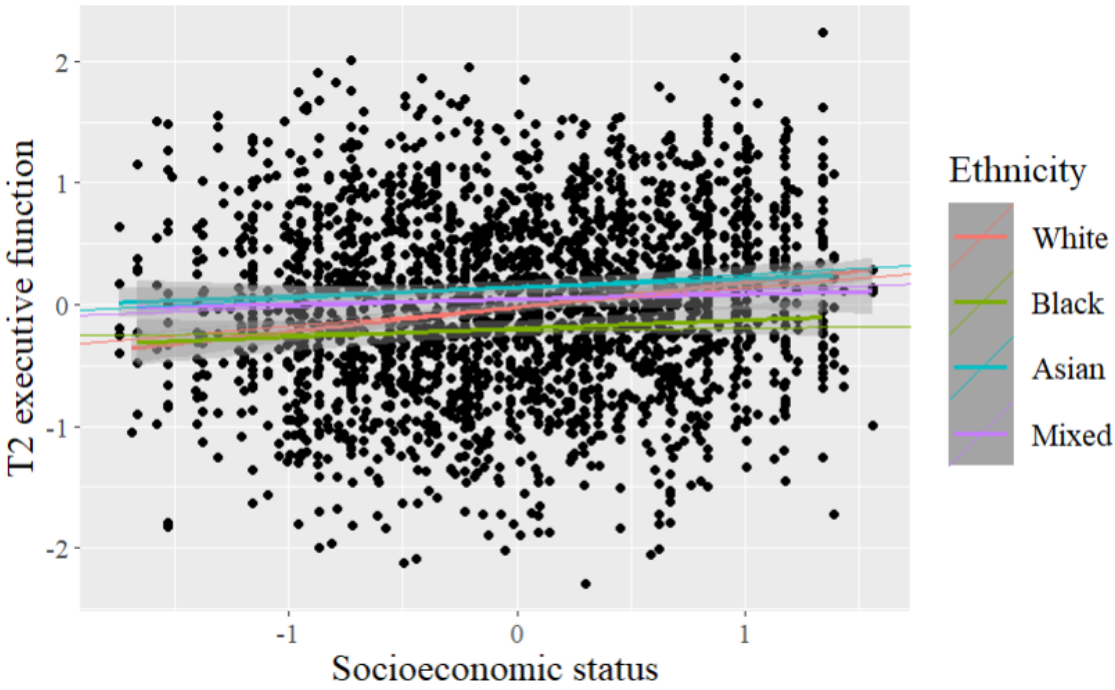
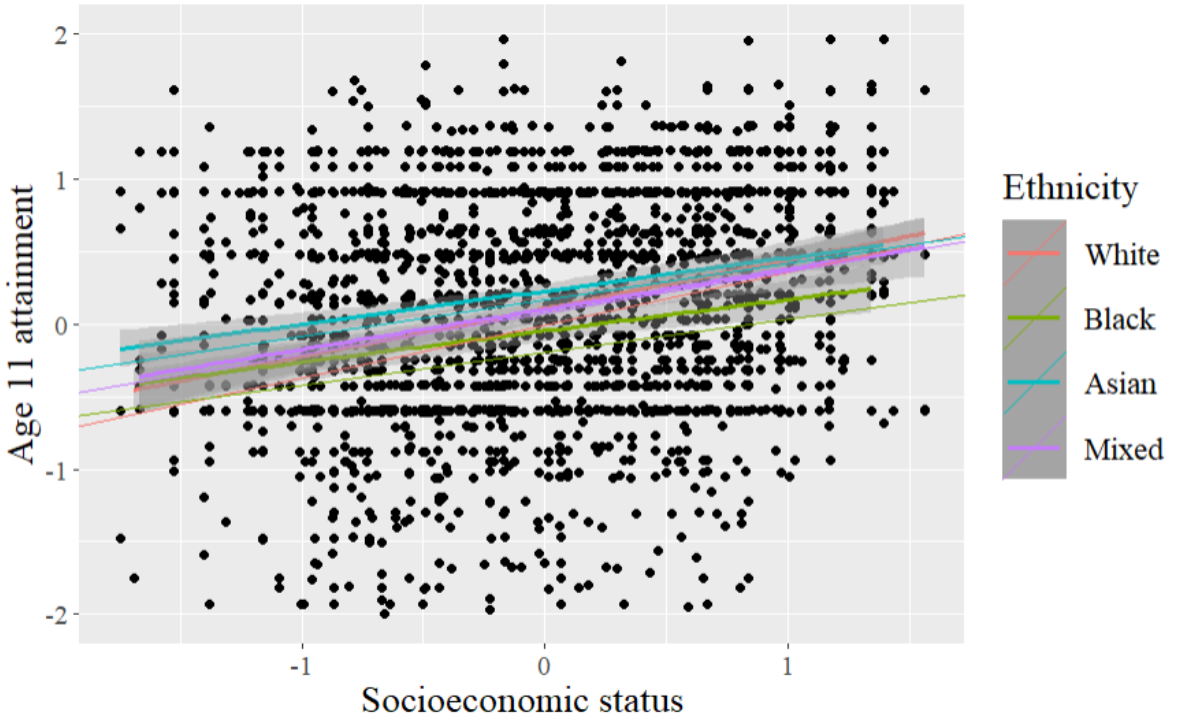


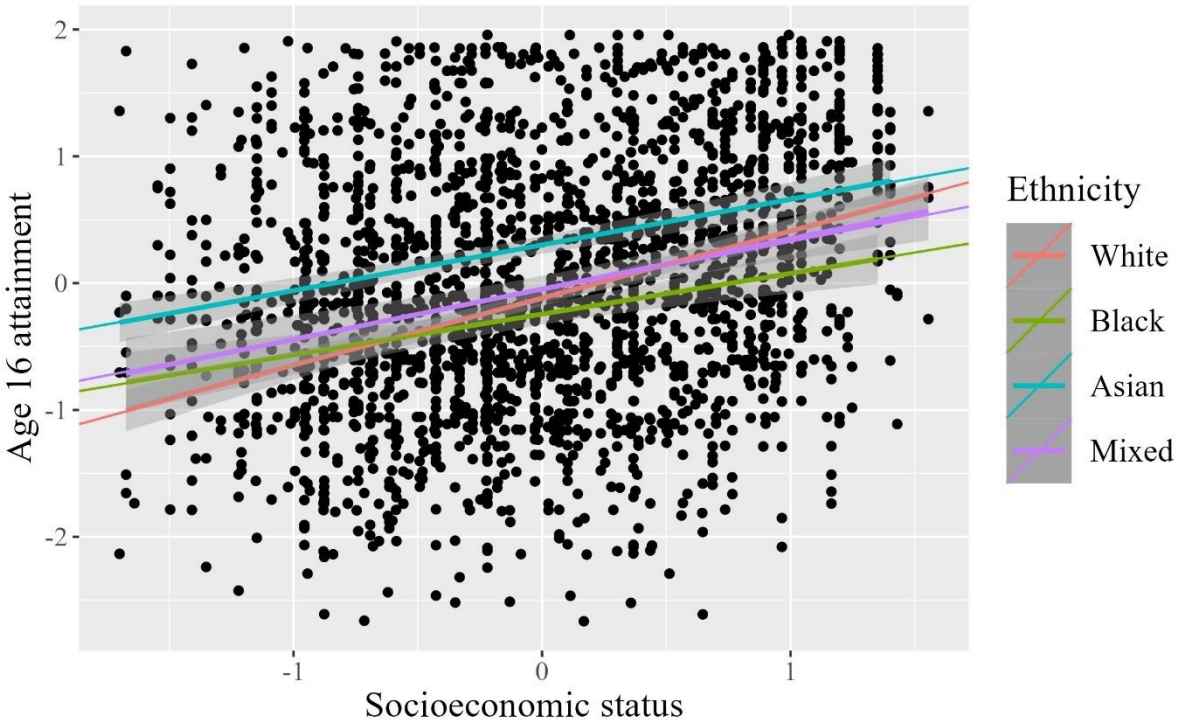
Figure 2.6

Scatterplots showing the associations between socioeconomic status and attainment at **a.** 11 years and **b. T2** 16 years (all factor scores) within different ethnicity groups.

a.



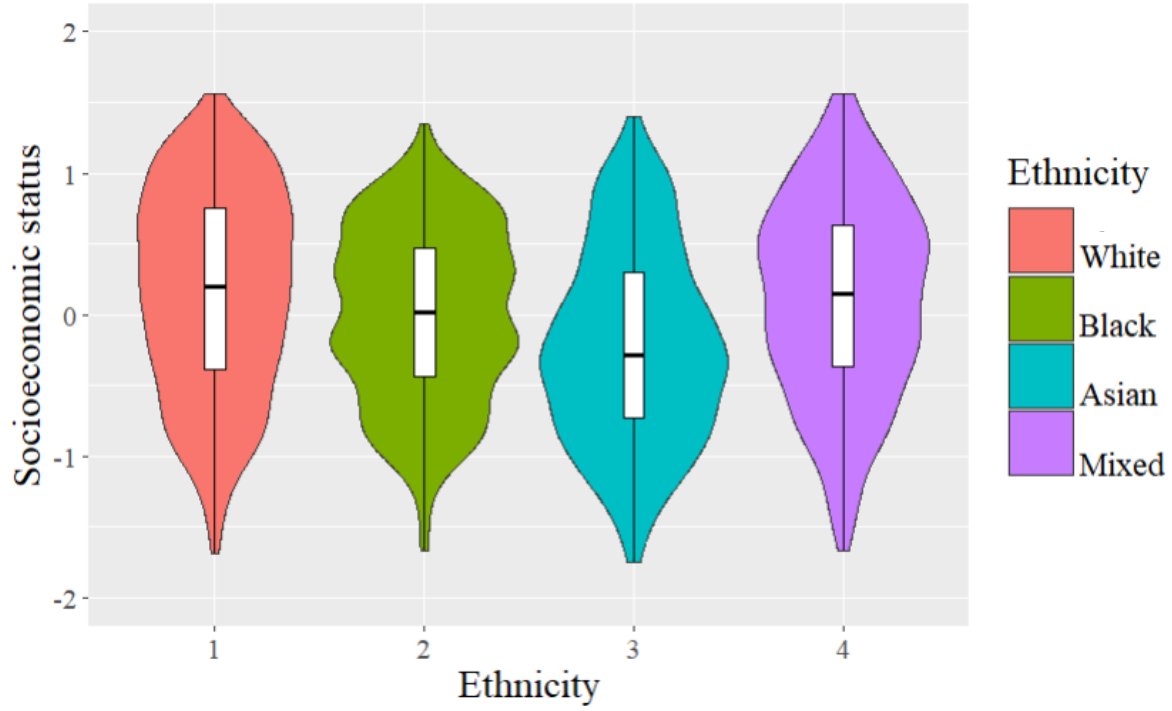
b.



Note. Grey shading around the lines shows 95% CIs.

Figure 2.7

Violin plot of the socioeconomic status factor score distribution within each ethnicity group.



Note. The Y axis shows the socioeconomic status factor.

2.4 Procedure

Participants completed the tasks and questionnaires as a whole class during their IT lessons in their school computer suites. They had the length of the scheduled class to complete the task battery. They were instructed to work through the tasks on their own, but researchers were available in case of technical issue or to clarify instructions.

Executive function tasks were always completed in the same order. The order of executive function task presentation was determined by the perceived usefulness of the measures for answering questions about development by the SCAMP team and feedback from participants in the pilot. Under the assumption that the number of participants failing to complete a task would increase in later tasks, this approach maximised participant numbers for the most important tasks with respect to a-priori hypotheses. It had the disadvantage of producing unequal participant numbers across the different tasks and potentially of

introducing order effects (e.g., due to fatigue). During the testing session, cognitive tasks and questionnaires alternated and were staggered in two different ways to reduce the possible influence of neighbouring pupils' responses and in an attempt to mitigate order effects (see **Chapter 2 Appendices: Appendix D**).

The TMT was prioritised, as it yields multiple measures of cognitive skills: in addition to being a validated cognitive flexibility measure, it yields measures of processing speed, visuospatial processing, and motor sequencing. Further, participants in the pilot found the task easy to understand and to be quite entertaining so it was felt that this would provide an engaging start to the battery. The BDS and SWM tasks were presented next since performance on working memory tasks shows continued improvement through adolescence according to previous studies and associations with school attainment. It was also deemed important to have large amounts of data on both verbal and visuospatial working memory skills. Corsi span was presented later, as, despite also being a well validated visuospatial working memory measure, it does not provide an additional strategy measure like SWM. The AX-CPT was presented last, as pilot participants reported that they found this task boring, and a low number of errors were expected due to the age of the participants.

Changes were made to the SCAMP battery over time, largely to improve upon earlier versions. Relevant to the current analyses are changes made to the BDS and CFT tasks after the first 403 participants completed the T1 assessment. In brief, additional repeats of certain conditions and a third CFT subtest were initially included but removed to shorten the duration of the testing battery, and the instructions of the BDS were clarified. Instructions presented before the practice trials were reworded to make clearer and stress that number sequences needed to be reversed. After 1,573 participants had completed T1 testing, a reminder that the number sequence needed to be reversed was also presented after the practice trials. Then, after the first 4,350 participants had completed T1 assessments, the Speech in Noise Task was

moved down in the battery and the program was edited. This was done to make it easier to skip this task in case of audio problems which had delayed or prevented some participants from completing earlier versions of the battery. This slight change in the order of tasks is reflected in the table in **Chapter 2 Appendices: Appendix D**. No further changes were made prior to or during T2 testing. Since no changes were made to the actual executive function tasks, or the order in which they were presented, I did not control for the version of the battery pupils were exposed to at T1.

2.5 Modelling approach

Throughout this thesis, I use lavaan's structural equation modelling function – sem() - to test my predictions. Structural equation modelling is a useful approach to understanding the generality or specificity of longitudinal associations between different constructs, since it can incorporate both observed (measured) and latent variables (underlying constructs). It is a confirmatory approach, allowing researchers to construct and test the plausibility of theoretical models. This is done by analysing how well the user constructed model fits with a given dataset by comparing the results of fit tests (which are based on the χ^2 test) to threshold values. A range of fit indices are available, but for the purpose of this thesis I report and interpret CFI and RMSEA. In section **2.7** I explain why these indices were chosen and which threshold values were used.

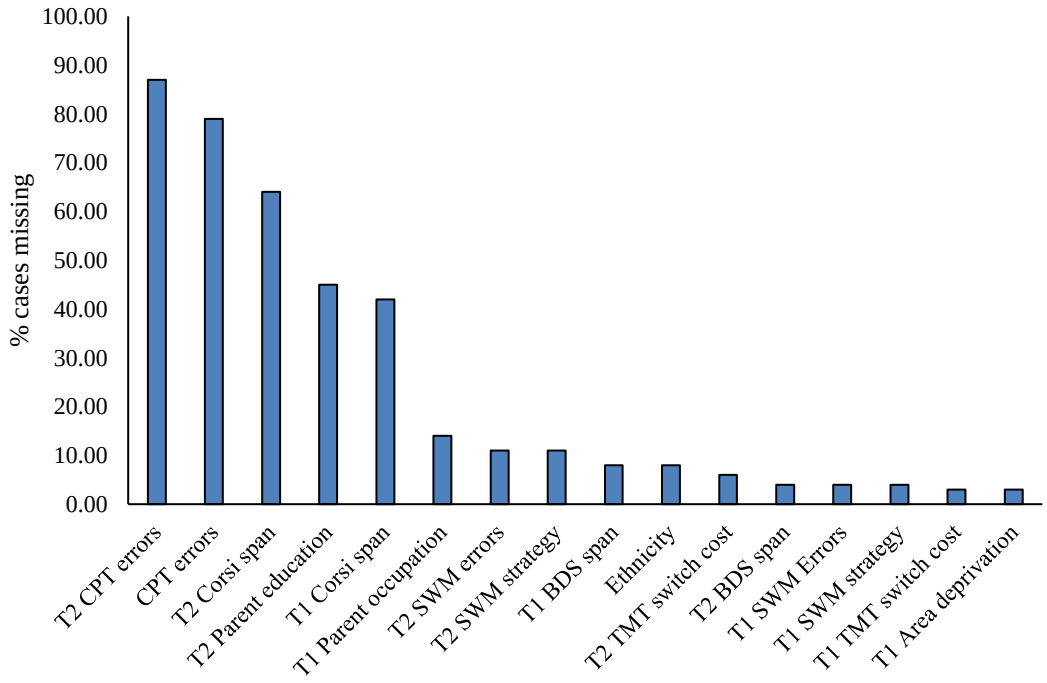
2.5.1 Missing data

There was no missing data on the National Pupil Database measures for the included subsample. However, due to self-report questions being optional, the fixed order of task presentation, and that there was limited time allocated to complete the assessment battery there are varying degrees of missingness across Psytools variables (see **Figure 2.8**). Most data were missing on the AX-CPT, followed by the parental occupation and income variables. Area deprivation had relatively little missing data. This is likely because area

deprivation was calculated based on the pupil's self-reported postcode whereas parental occupation and income required a direct self-report about family socioeconomic status. Some participants may not have had knowledge of their parents' educational and occupational statuses or may have felt uncomfortable disclosing this information. n for the executive function measures largely decreased in line with the order of testing (e.g., n_{T1} = 2,636 for the first executive function measure and n_{T1} = 586 for the last executive function measure), with exceptions possibly due to the different exclusion criteria for different measures (see section **2.3.2** for details). Missingness was slightly greater on the T2 executive function measures, perhaps because some participants were not willing to engage with the measures at T2 having previously completed them a few years earlier.

Figure 2.8

Bar graph showing the percentage of datapoints missing across different Psytools measures.

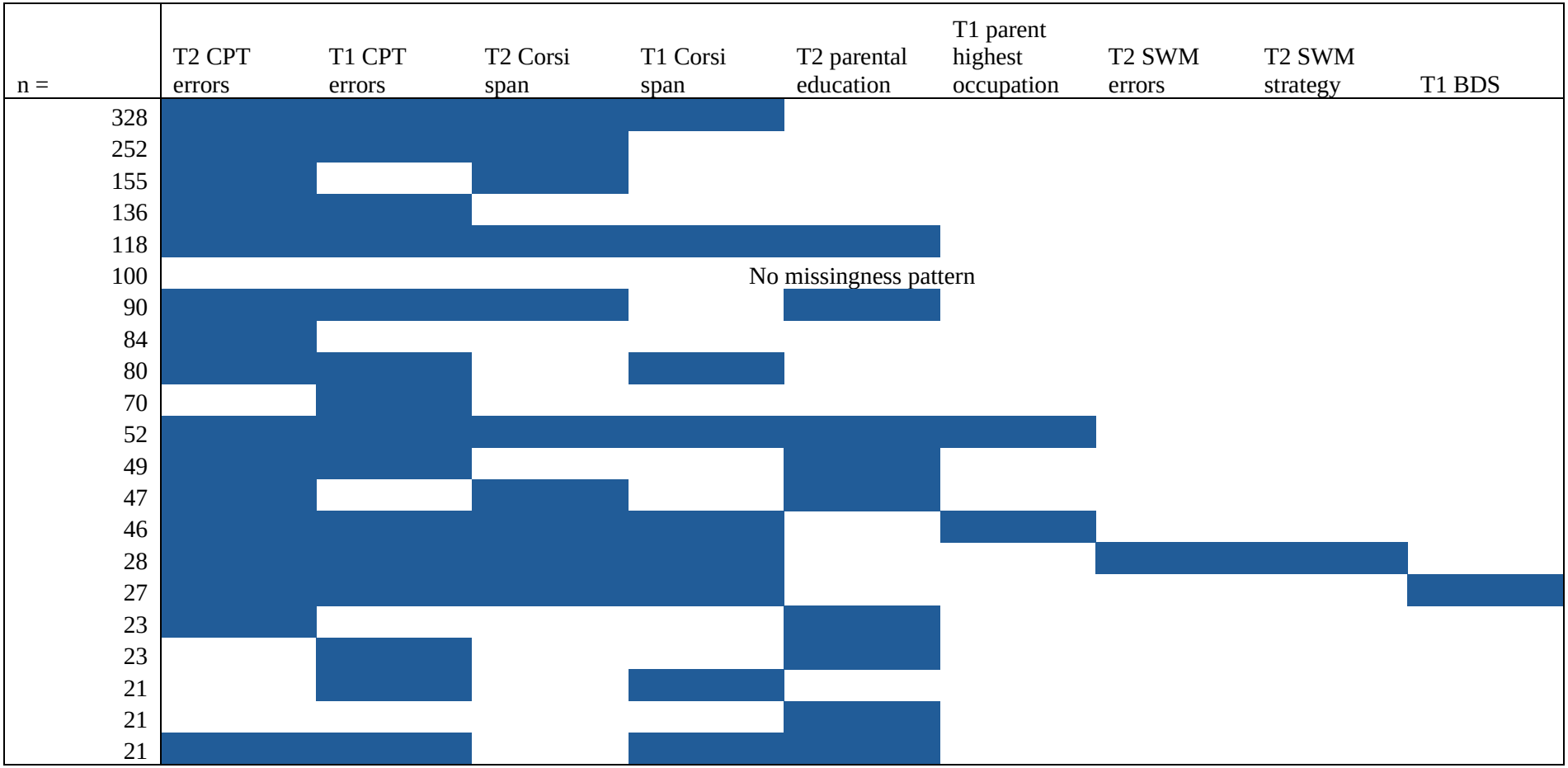


Note. Psytools variables with 0% or <.05% missingness are not shown here.

There were 397 different missingness patterns in the Psytools measures, 232 of which were unique to individual participants. A further 144 patterns of missingness were shared by between only 2-20 participants. **Table 2.4** shows the 21 patterns of missingness which were present for >20 participants. The most common pattern was missingness on T1 and T2 AX-CPT errors and Corsi span, which was present for 12% of the included participants. This was followed by missingness on the two AX-CPT variables and T2 Corsi span, just T2 AX-CPT errors and Corsi span, both AX-CPT errors measures, and then on both AX-CPT and both Corsi measures plus parental education. Together, these 5 patterns account for the missingness patterns in 36% of the sample. No missingness was the 6th most common pattern. Missingness on T1 and/or T2 AX-CPT errors was seen across all but 2 of the 21 most common patterns (one of which being the no missingness pattern). By contrast, missingness on both parental education and occupation was only seen in 1 of the 21 most frequent patterns, with 52 participants showing this pattern of missingness. This suggests that these variables are not systematically missing due to participants not wishing to disclose their family socioeconomic circumstances in most participants. Other than the aforementioned measures, only T1 BDS and T2 SWM errors and strategy appeared in any of the missingness patterns present in >20 cases.

Table 2.4

Missingness patterns present in >20 participants in the SCAMP subsample.



Note. BDS = Backwards Digit Span; SWM = Spatial Working Memory; CPT = Continuous Performance Task. For ease of the reader's interpretation, only measures that were involved in any of these most frequent patterns are shown here.

Structural equation modelling offers an effective way to deal with missing data in full information maximum likelihood (FIML) estimation. Maximum likelihood estimation finds the values of model parameters that maximise the probability of the observed data. FIML is a form of maximum likelihood estimation that uses all available data in parameter estimation, hence "full information". Estimates are refined iteratively until the algorithm converges on the best fitting values for the whole dataset. I opted to use this approach to dealing with missing data in all models, given its relative advantages over other methods and the scale of the missing data problem amongst the Psytools measures (see **Figure 2.8**).

FIML assumes a normal distribution and is intended for analysis of normally distributed continuous variables with missingness completely at random or at random. FIML is generally recommended for use with this type of data over deletion because it preserves the structure of the data, whilst deletion can result in a biased sample and lower statistical power. FIML is also often preferred over multiple imputation as it is more efficient and performs better than imputation when data are not missing completely at random (Graham et al., 1996; Newman, 2003). FIML has also been shown to outperform multiple imputation when data have second level dependencies (Larsen, 2011).

Robust FIML (which uses sandwich covariance estimation to compute standard errors) also outperforms multiple imputation and Bayesian methods in estimating models with dichotomous variables (Jia, 2016). Since most of my control variables, as well as some predictors, are binary or dummy variables I adopt this approach. FIML also performs as well as diagonal weighted least squares estimation in the case of models with both continuous and categorical variables run on large samples (Li, 2021) with the relative advantages of preserving statistical power and allowing for interpretation of model fit based on conventional criteria (Shi & Maydeu-Olivares, 2020).

As a follow up step, with full model outputs reported in **Chapter 3 Appendices D** and **E** and **Chapter 4 Appendices D and G**, auxiliary variables were added to the structural equation models. Auxiliary variables are measures that predict missingness on the key variables in the model. The saturated correlates approach to including auxiliary variables in structural equation models run with FIML estimation has been shown to reduce bias in parameter and model fit estimation (Graham, 2003). I therefore adopted this approach to model specification. The saturated correlates approach stipulates that a) in the case of exogeneous observed variables containing missingness, auxiliary variables are correlated with the observed variables themselves; b) in the case of observed variables that make up latent factors or observed variables which are predicted by other variables in the specified model, auxiliary variables are correlated with the residuals of these variables; c) that all auxiliary variables are correlated with one another. Three auxiliary variables were included in the models:

Duration of testing sessions

Participants had the length of their timetabled ICT lesson to complete the assessment battery, with sessions ranging from 41.25 – 84.22 minutes at T1 and 40.25 – 138.50 minutes at T2. Session duration was expected to strongly associate with non-completion of the latter cognitive tasks, but I also expected that participants in school with shorter sessions may have felt they needed to skip through self-report questions to get to the end of the assessment battery. Hence, this measure was included as a continuous covariate of both the Psytools socioeconomic status indicators and the executive function measures.

Percentage of pupils in receipt of Free School Meals at the school level

Percentages of pupils on Free School Meals per school ranged from 12 - 47.4%. I anticipated that pupils from lower socioeconomic status backgrounds and those from single

parent families would be less likely to report their parents' occupation and education levels. They may have felt uncomfortable disclosing this information, or in the case of the latter group may not have known this information about their non-cohabiting parent or understood whether they should disclose information about the non-cohabiting parent. Free School Meals status should capture both types of pupil. I also reasoned that there may have been more off task behaviour in schools with high rates of pupils on Free School Meals since pupils from schools with high intakes of pupils from low socioeconomic status backgrounds are more likely to experience behavioural challenges (Flouri & Midouhas, 2016). Hence, this auxiliary variable was also included as a continuous covariate of the Psytools socioeconomic status indicators and the executive function measures.

School type

In the UK, there are four different types of state school: Community schools, otherwise known as local authority-maintained schools, have no input from trusts or religious organisations. Three of the schools represented by the included participants were community schools. Foundation and voluntary schools are local authority funded, often with support from religious bodies, but the local authority has less control over the running of these schools compared to community schools. Four schools in the included subsample were foundation or voluntary schools. Academies and free schools, by contrast, are not local authority maintained and instead are run by not-for-profit organisations known as academy trusts. The majority (16 schools) of SCAMP schools included in my analyses were academy schools, consistent with the national picture (Local Government Association, 2023). Finally, grammar schools can fall into any of these categories of management but differ from the three former types in that they select pupils based on academic ability. No SCAMP pupils were educated in grammar schools.

I expected that school type would be related to missingness on all Psytools measures as it determines the control schools have over resource allocation, influencing for example class size and the quality of the IT equipment, which could contribute to participants' level of focus and ability to engage with the tasks during the testing sessions. School type was therefore included as a factor, with the most populous category used as the reference category. The two school type factors were covaried with both the socioeconomic status indicators and the executive function measures.

2.5.2 Running regression models using lavaan's sem() function

Chapter 3 uses multiple regression to answer questions about generality versus specificity of socioeconomic status to attainment relationships. These analyses were still run in lavaan's sem() function so that I could maximise power by applying the sem() FIML estimation method. This was important, given the large amount of missing data on some of the socioeconomic status and executive function measures (**Figure 2.8**). sem() accommodates multiple regression models but they are always just identified. This means that $\chi 2$, RMSEA and CFI/TLI values are not interpretable for multiple regression models run in sem().

I opted for regression to test these predictions rather than structural equation modelling for comparability with most other adolescent studies (e.g., Madhushanthi et al., 2020; Mance et al., 2019; Pluck et al., 2021; Sutin et al., 2022). Multiple regression can be thought of as essentially a simpler form of structural equation modelling which includes only a single dependent variable and no measurement model (the part where latent factors are specified). However, most of the analyses in **Chapter 3** also include latent factors. These were modelled in keeping with multiple regression (i.e., structural model only), by saving latent factors created through confirmatory factor analysis and entering the saved values as predictors in the models. This approach has the added benefit of reducing model complexity,

relative to structural equation models where latent factors are defined within the sem() command, thereby further maximising statistical power.

2.5.3 Why use linear models?

Linear modelling is overwhelmingly the most common approach in the literature (e.g., in Mousavi et al. only 1/16 studies took a non-linear modelling approach to understanding socioeconomic status to executive function associations) and studies from across the globe show that socioeconomic gradients in executive function skills and educational attainment are apparent at the group level during childhood (Anders & Jerrim, 2017; Bickel et al., 2014; Conway et al., 2018; Fernald et al., 2011; Howard et al., 2020; Noble et al., 2007). Linear solutions are more easily interpretable in real world terms than non-linear solutions (Long & Freese, 2006); one can conclude, the effect of a 1 SD increase on the outcome variable. The greater communicability of linear solutions to a non-scientific audience is valuable for research with potential policy implications. Further, non-linear models are more sensitive to noise in the data and are prone to overfitting (Lever et al., 2016). Therefore, linear models are a sensible option for relatively novel research and provide a starting point from which further research can understand the precise nature of relationships between constructs.

2.6 Data cleaning and assumption checks

All data cleaning steps and analyses were run in RStudio 2023.06.1+524. I excluded extreme outliers for the executive function tasks and CFT, defined ±3.29 SDs from the mean score on a given cognitive test, a range that should include 99.9% of normally distributed data (Field, 2009). This resulted in the exclusion of the following number of datapoints: TMT, T1: 26 participants, T2: 32; BDS, T1: 7, T2: 4; SWM errors, T1: 7, T2: 8; SWM strategy, T1: 4, T2: 2; Corsi: T1: 2, T2: 0; CPT: T1: 12, T2: 8; CFT, T1: 2, T2: 5.

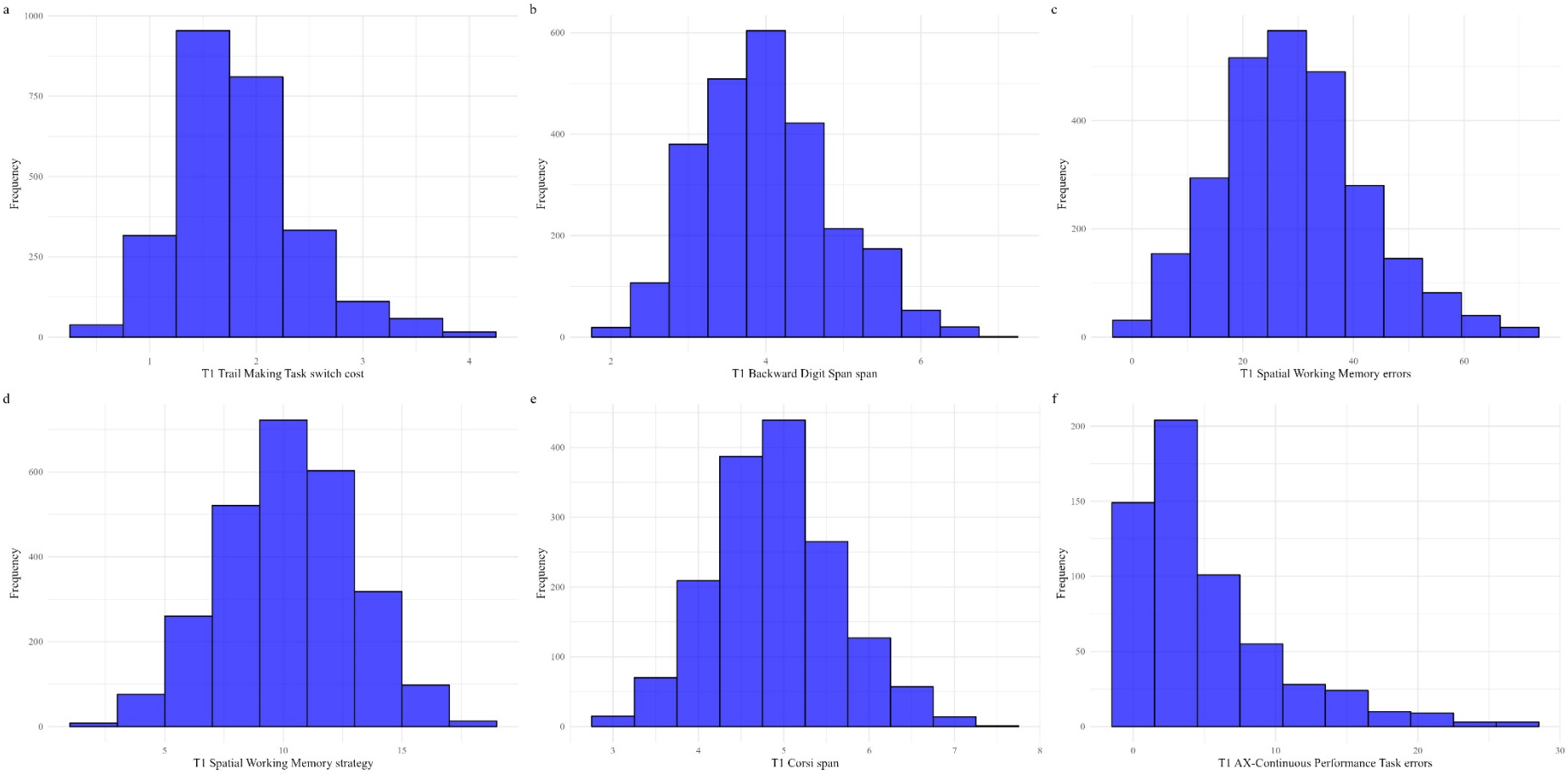
2.6.1 Assessing the distribution of continuous variables

Parameter estimates derived from models using maximum likelihood estimation have been shown to be relatively unaffected by departures from normality (Finch et al., 1997), but non-normality increases the likelihood of type 1 error in parameter testing (Curran et al., 1996; Hu et al., 1992). All executive function measures except CPT errors followed a roughly normal distribution of scores (see **Figure 2.9** for histogram matrices). I therefore proceeded with FIML estimation, but with scaled chi-square and robust standard errors corrections to account for the inflation of type 1 error in parameter tests as suggested by Satorra (1988) and Satorra and Bentler (1994). This approach has been shown to perform well under a variety of different distributional conditions (Curran et al., 1996; Hu et al., 1992).

Figure 2.9

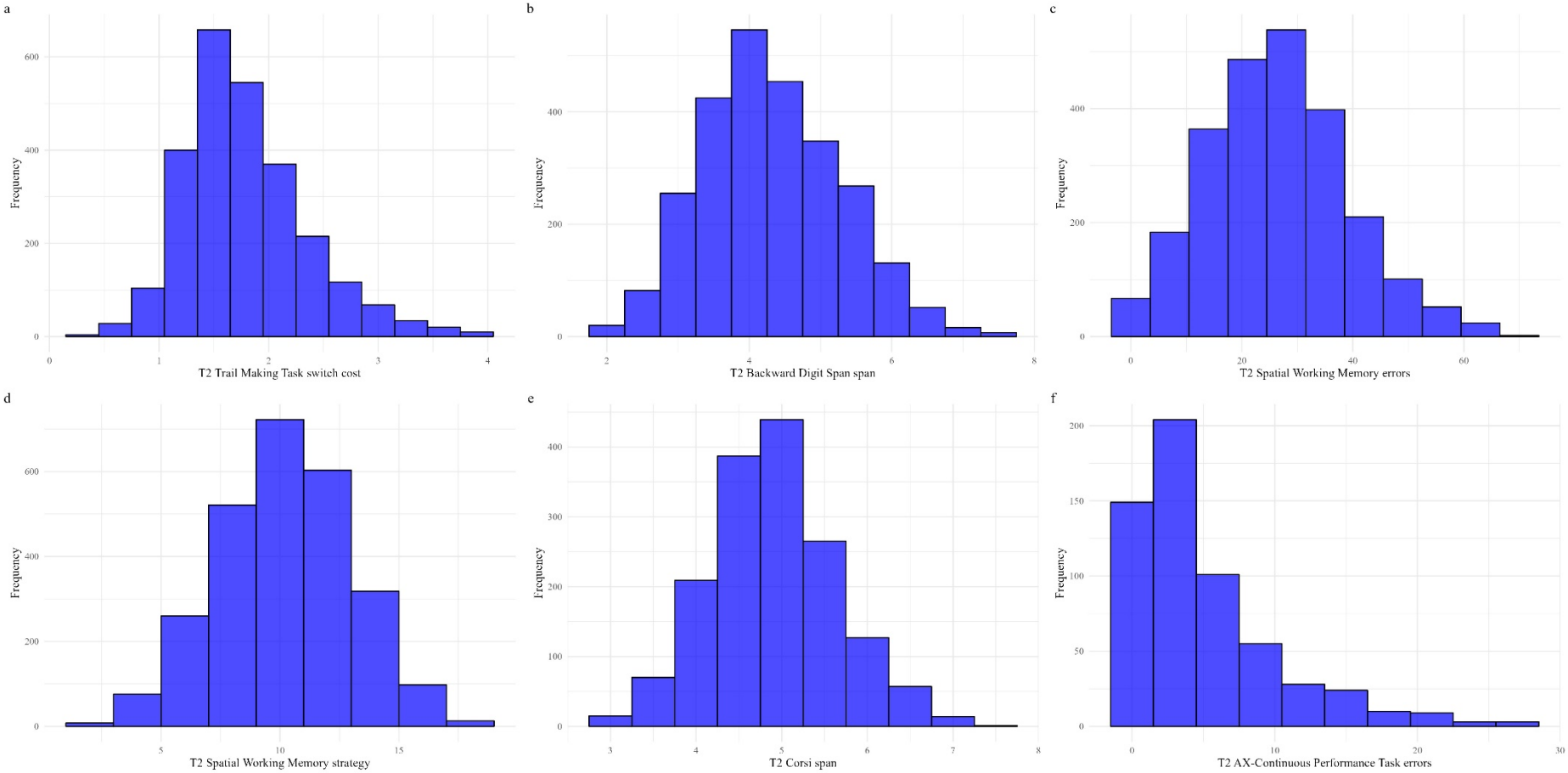
Histogram matrix of the score distributions of a. Trail Making Task switch cost, b. Backward Digit Span span, c. Spatial Working Memory errors, d. Spatial Working Memory strategy, e. Corsi span and d. AX-Continuous Performance Task errors at **a.** T1 and **b.** T2.

a.



Histogram matrix of the score distributions of a. Trail Making Task switch cost, b. Backward Digit Span span, c. Spatial Working Memory errors, d. Spatial Working Memory strategy, e. Corsi span and d. AX-Continuous Performance Task errors at T2.

b.



2.6.2 Treatment of non-continuous variables

Socioeconomic status indices were coded as either binary (FSM status), ordinal (parent highest level of occupation and area level deprivation), or interval (number of parents who attended university). Some researchers have raised concerns about treating ordinal predictors as continuous in regression models, since the spacing between different levels of ordinal variables may not be consistent. I therefore ran a series of univariate regression models, predicting different executive function measures at T1 either treating the ordinal predictors as either continuous or categorical. I then checked whether treating predictors as continuous worsened model fit by comparing continuous and categorical model fits using likelihood ratio tests as per the suggestions of Williams (2021). The difference was non-significant in all cases (**Table 2.5**). Hence, I opted to treat them as continuous in all models, given the greater ease of interpretability afforded by this type of model (Long & Freese, 2006) and the fact that models where ordinal variables are treated as continuous rarely miss effects that would be picked up by a model treating them as categorical (Pasta, 2009).

Ethnicity and first language status were dummy coded, since lavaan's sem() function cannot accept variables treated as categorical with more than two levels. The most populous categories (white and monolingual English) were used as the reference categories unless otherwise stated.

Table 2.5

Results of likelihood ratio tests comparing univariate regression models treating parent highest occupation as either categorical or continuous predictors.

	Parent highest occupation			Area level deprivation		
	Log likelihood continuous	Log likelihood categorical		Log likelihood continuous	Log likelihood categorical	
~ TMT switch	-1940.4	-1935.7	$\chi^2 = 9.44$, $p = .150$	-2234.0	-2232.8	$\chi^2 = 2.47$, $p = .482$
~ BDS span	-2712.5	-2710.8	$\chi^2 = 3.28$, $p = .773$	-3075.2	-3074.2	$\chi^2 = 1.94$, $p = .586$
~ SWM errors	-9028.1	-9026.4	$\chi^2 = 3.41$, $p = .755$	-10165	-10164	$\chi^2 = 0.42$, $p = .936$
~ SWM strategy	-5559.7	-5558.3	$\chi^2 = 2.75$, $p = .839$	-6264.6	-6263.8	$\chi^2 = 1.58$, $p = .665$
~ Corsi span	-1633.2	-1631.1	$\chi^2 = 4.07$, $p = .668$	-1752.2	-1750.8	$\chi^2 = 2.81$, $p = .421$
~ CPT errors	-1661.5	-1657.7	$\chi^2 = 7.57$, $p = .271$	-1765.1	-1764.0	$\chi^2 = 2.31$, $p = .510$

Note. DF = 3 for the continuous treatment of parent highest occupation and area deprivation and 9 and 6 for the categorical treatment of these variables, respectively

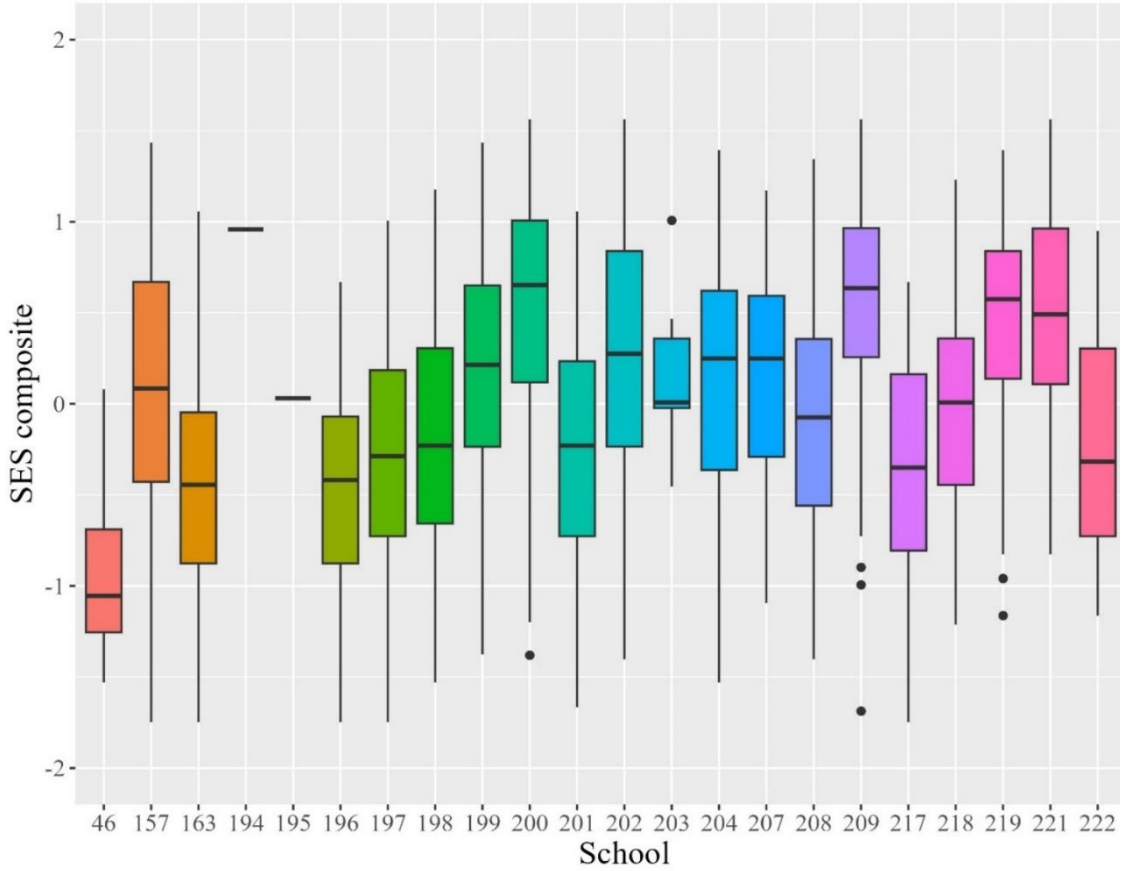
2.6.3 Accounting for clustering in the sample

Participants in the SCAMP subsample came from 24 different schools. To quantify what proportion of GCSE attainment was explained by shared school context, I calculated the intraclass coefficient between school ID and the GCSE factor. The ICC was .10 which is above the widely used .05 threshold (e.g., Leonardo & Carla, 2005, as cited in Kianoush & Masoomehnikbakht, 2015). I then tested whether clustering would affect the accuracy of standard error estimates, by calculating the square root of the design effect: $\sqrt{1 + (m - 1) * ICC}$, where m is the average cluster size (118). The design effect was 3.56, indicating that standard errors would be 3 and a half times larger accounting for clustering compared to if observations were treated as independent.

I therefore decided to control for the school effect using Huber-White estimated robust standard errors. This is a sandwich estimator, which adjusts standard errors to correct for heteroscedasticity and correlations in the data. I opted for this approach, as opposed to multilevel modelling or fixed effects modelling, following the advice set out in McNeish (2023). As I was only interested in correcting for the inflation of type 1 errors due to violation of heteroscedasticity assumptions and school effects were not directly related to the research questions, I deemed this approach sufficient. Multilevel modelling was not appropriate as estimation issues are common when it is applied to datasets with fewer than 30 clusters. Also, some clusters contained very few participants and therefore low to null within-cluster variance in socioeconomic status and attainment so fixed effect modelling would not be appropriate (see McNeish & Kelley, 2019 and **Figure 2.10**).

Figure 2.10

Box plots showing the socioeconomic status distribution within different schools.



Note. The x axis gives the school ID. The y axis gives the socioeconomic status factor score. Distributions are shown for the state schools participating in the SCAMP study.

2.7 Assessing model fit

Throughout, I report robust CFI and RMSEA estimates to correct for inflation of type two error due to data non-normality (Savalei, 2018). Given the exploratory nature of this work, CFI was chosen rather than TLI, as it has less of a penalty for model complexity. Though there is some disagreement about specific threshold values for acceptable fit, these all suggest that values for CFI of < .90 and for RMSEA of > .10 indicate poor fit (Browne & Cudeck, 1992; Hu & Bentler, 1999; Schumacker & Lomax, 2010). I therefore use these values as my cut offs. I do not report χ^2, as it severely over-rejects models run on large samples (Bentler & Bonett, 1980; Jöreskog & Sörbom, 1993) and is widely thought to be an unreliable indicator of model fit in the presence of a high *N*.

Chapter 3: Longitudinal associations between socioeconomic status and executive function during adolescence are small and specific

3.1 Introduction

Individual differences in executive function skills are associated with a host of educational, health, and occupational outcomes (Ahmed et al., 2019; Galioto et al., 2018; Letkiewicz et al., 2014). Globally, within-countries, a socioeconomic status gradient in executive function is seen whereby children and adolescents from deprived backgrounds perform worse on measures of executive function than their peers (Bickel et al., 2014; Conway et al., 2018; Fatima & Sheikh, 2014; Fernald et al., 2011; Howard et al., 2020; Madhushanthi et al., 2020; Noble et al., 2007). However, socioeconomic status is a multifaceted construct with different aspects potentially conferring unique resources and opportunities to children and young people (Duncan & Magnuson, 2002; Davis-Kean et al., 2021). It is therefore important to interrogate which aspects of socioeconomic status are associated with executive function development.

The developmental literature focuses most often on parental income and parental level of education in relation to executive function skills (e.g., Conway et al., 2018; Fernald et al., 2011), whilst factors such as area-level deprivation are less frequently studied. Given the multifaceted nature of socioeconomic status, there are many different mechanisms through which it could affect brain and cognitive development. These include prenatal effects (e.g., genetic, nutritional, maternal stress, exposure to teratogens), levels of exposure to chronic stress, cognitive stimulation (e.g., through academic tutoring, playing musical instruments or sports), nurturing, and pollutants (e.g., lead, noise, pesticide and other neurotoxins; Herting et al., 2019; McLaughlin et al., 2014; Thomas & Coecke, 2023). Focusing on the same few individual level indices of socioeconomic status is therefore problematic as the complexity of the relationship between specific socioeconomic status indices and executive functions may not be adequately captured.

Several recent neuroimaging studies have highlighted the potential significance of often overlooked neighbourhood level socioeconomic status factors. A large scale study of 8–23 year-olds from Philadelphia showed that area-level deprivation, measured as a weighted factor score of census-derived data (e.g., median family income, percent people in poverty, percent of residents who are married) in the local area, was associated with lower activation of fronto-parietal task-relevant brain regions during a 2-back task, including when controlling for parental education (Murtha et al., 2022). Rakesh and colleagues (2021) have documented more widespread alterations in brain activity that appear to be linked to area-level deprivation in another US sample, aged 9–11 years. Neighbourhood deprivation was related to lower between- and within-network resting state functional connectivity in sensorimotor and higher-order networks (e.g., default mode; dorsal attention), and these differences in connectivity were significantly predictive of executive function task performance, measured by a baseline cognitive task battery. Area-level deprivation may therefore be a dimension of socioeconomic status with important consequences for executive function development, in addition to parental education and income/occupation. As both studies were cross-sectional, further evidence is needed to determine *when* area-level deprivation may be meaningfully related to executive function development.

Studies have predominantly focused on socioeconomic status associations with developing cognitive skills in early childhood despite neuroimaging evidence indicating that the regions supporting executive functions show significant progressive and regressive structural changes into the early 20s (Crone & Dahl, 2012; Murty et al., 2016; see Thomas & Coecke, 2023, for links between brain structure and function in the context of socioeconomic status). In line with the timing of these neural changes, performance on many executive measures improves with age for the first two decades of life (Huizinga et al., 2006; Simmonds et al., 2017; Steinberg et al., 2018; Tamnes et al., 2010). Crucially, development

of frontal brain regions appears to be more strongly related to individual socioeconomic background than other brain regions (Noble et al., 2015). Therefore, it is necessary to expand the study of relationships between socioeconomic status and executive function development into adolescence.

Behavioural studies of children from Australia, South America, South Africa, and the United States all report a socioeconomic status gradient for executive function performance, whereby the poorest perform worse on cognitive measures (Bickel et al., 2014; Conway et al., 2018; Fernald et al., 2011; Howard et al., 2020; Noble et al., 2007). However, note that cross-country comparison research has shown that the direction of the difference between countries in relative economic development does not necessarily align with the direction of the difference in average executive function skills of children living in those countries (Howard et al., 2020). Effect sizes are overall small to moderate according to a recent meta-analysis (which mostly included studies of early childhood), but larger when study samples are more socioeconomically diverse (Lawson et al., 2018).

3.1.1 Socioeconomic status and executive function in adolescence

However, the available adolescent literature is somewhat less consistent. A significant positive association between a composite socioeconomic status measure and Delis-Kaplan Executive Function System composite score (DKEFS; Delis et al., 2001) was seen in a cross-sectional study of 512 13–19-year-old adolescents from Pakistan (Fatima & Sheikh, 2014). Similar results were observed in a cross-sectional study of 110 12–17-year-old Ecuadorian teenagers using the DKEFS composite score as an outcome (Pluck et al., 2021). In contrast, Mance et al. (2019) found no significant associations between a composite measure of socioeconomic status and shifting abilities, behavioural regulation, or inhibitory control as assessed by the Behavior Rating Inventory of Executive Function questionnaire (BRIEF; Gioia et al., 2000) in a cross-sectional study of 267 urban US adolescents aged 11–17 years.

If individual differences in socioeconomic status continue to predict executive function skills during adolescence, there is a lack of clarity in the literature about which indices of socioeconomic status are most relevant for executive function associations in which developmental period. Some possible mechanisms through which socioeconomic status might affect cognitive development would be expected to impact the development of the whole brain (see Johnson et al., 2021, for a discussion of this). For example, being overweight (which occurs more frequently in low socioeconomic status families in the West) has been shown to be related to reduced white matter integrity across the whole brain (Verstynen et al., 2012). By contrast, it has recently been argued by a number of researchers (e.g., Amir et al., 2018; Frankenhuis & Nettle, 2020; Mittal et al., 2015) that adverse experiences during development, such as growing up in poverty, are unlikely to have universal negative impacts on cognitive skills. Instead, cognitive skills are thought to develop adaptively in response to socioeconomic status-related environmental pressures. Hence, the relevance of the cognitive skill in question to functioning in the individual's environment is thought to influence how it develops. This leads to the prediction that socioeconomic status relationships are specific to certain executive functions. A better understanding of the specificity or generality of associations between socioeconomic status and executive function during adolescence would help to inform intervention targets to mitigate the possible downstream consequences of socioeconomic status-related factors on education and adult life outcomes.

Results from a meta-analysis of studies of 2−18-year-olds by Lawson et al. (2018) suggest that general associations between socioeconomic status and executive function may be more likely than specific associations, at least in childhood. Studies using composite measures of executive function showed the largest socioeconomic status effect sizes (r = .28), followed by working memory measures (working memory; r = .18), attention shifting (r =

.17), inhibitory control (r = .14), and other abilities such as planning (r = .09). Convergent results in predominantly childhood samples were reported by Tucker-Drob (2013), who found that parental education level had non-specific relationships with different cognitive measures and by Bignardi et al. (2024), who found a moderate association between an socioeconomic status composite and general cognitive ability using data from three cohort studies, whilst associations with specific executive function measures were mostly small and non-significant or inconsistent across cohorts. However, Lawson et al. (2018) suggest that stronger general than specific associations could be observed because composite measures are more reliable than individual executive function measures in young children. The more psychometrically robust executive function measures available for adolescents may allow a better differentiation of specific vs. general socioeconomic status – executive function associations.

There are several reasons to suppose that there may be social inequalities in developing executive function skills during adolescence, and that adolescents may show greater specificity of socioeconomic status – executive function associations than children. First, there is some evidence that executive functions become more differentiated over the course of adolescence (Karr et al., 2018; Lee et al., 2013). Moreover, since socioeconomic status tends to remain stable (Hackman et al., 2015), by adolescence there may be a cumulative effect of familial relative socioeconomic standing, making the effects of factors related to different aspects of socioeconomic status more pronounced in adolescents than in children. Different aspects of socioeconomic status may also differentially affect executive function development during childhood compared to adolescence. During adolescence, the influence of parents relative to peers on decision making decreases (Icenogle & Cauffman, 2021) so socioeconomic status factors outside of the family could potentially become more important at this stage. Research comparing the relative predictive power of multiple indices

of familial socioeconomic status and systems-level socioeconomic status (e.g., school; area-level) in adolescence is therefore needed to inform our understanding of specific socioeconomic status-executive function associations that may emerge during adolescence compared to childhood.

Three studies have looked at specific socioeconomic status-executive function associations during adolescence. In a sample of 4,164 Australian adolescents, Sutin et al. (2022) found both family and neighbourhood level socioeconomic status at 10−11 years were positively associated with attention skills at 14−15 years, but only family-level socioeconomic status predicted error monitoring and only area-level socioeconomic status predicted working memory. These results provide some evidence for both specific and general associations between socioeconomic status and executive function. However, the analyses did not control for executive function at age 10–11, so they may have been driven by socioeconomic status-related effects in childhood. Moreover, familial and neighbourhood level socioeconomic status were not considered in the same analysis, so the results do not account for the correlation between different aspects of socioeconomic status. Donati et al. (2019) analysed data on over 5,000 adolescents and showed that working memory was moderately positively correlated (r = .29), and inhibitory control weakly negatively correlated (r = -.07), with parental occupation. By contrast, in a cross-sectional sample of 200 female Sri Lankan adolescents, Madhushanthi et al. (2020) found that maternal and paternal education levels were significant predictors of working memory (Wechsler, 2003) and that maternal education also positively predicted inhibitory control. However, parental occupation and household income were not significant predictors of either executive function, and socioeconomic status disparities did not associate with a separate computerised measure of visuospatial working memory. Differences in findings may be due to differences in sample size, or distribution of parental occupation in different samples and countries.

3.1.2 Aims and hypotheses

Here I report multiple regression analyses of socioeconomic status and cognitive data from the UK Study of Cognition, Adolescents and Mobile Phones (SCAMP; https://scampstudy.org/). I extended work by Filippi et al. (2022) which found a significant main effect of a composite measure of socioeconomic status on executive function measures in a subset of the SCAMP cohort, to explore the relative predictive power of different indices of socioeconomic status (parental education, parental occupation, area level deprivation, Free School Meals status) for specific executive function outcomes.

Based on the evidence for socioeconomic status-executive function associations in childhood, I predicted that socioeconomic status would significantly predict executive function cross-sectionally in early adolescence (*M* age = 12 years) (H1) and that socioeconomic status would longitudinally associate with development of executive function into mid-adolescence (*M* age = 14 years) controlling for executive function at age 12 years (H2). Socioeconomic status-executive function associations were compared with associations between socioeconomic status and more general measures of cognition, namely non-verbal reasoning and language ability, which have both been shown to associate with socioeconomic status in childhood (e.g., Booth et al., 2010; van der Sluis et al., 2007).

I further predicted that different socioeconomic status indices would show some specific associations with executive function during adolescence (H3), and that socioeconomic status may differentially associate with specific executive functions (H4) as per Donati et al. (2019), Madhushanthi et al. (2020) and Sutin et al. (2022) and since executive functions are thought to become more differentiated through adolescence (Karr et al., 2018; Lee et al., 2013). I did not make any predictions about the nature of specific associations, given the limited and inconsistent research done with this age group and some of the socioeconomic status indices I had available.

3.2 Methods

The SCAMP subsample who contributed data to this study are described in **Chapter 2** - section **2.2.3.** Please see **Chapter 2** section **2.4** for details on the socioeconomic status indices and executive function measures included in these analyses.

3.2.1 Analysis plan

Multiple regression analyses with full information maximum likelihood estimation and robust standard errors were used to predict performance on executive function measures cross-sectionally at T1 from the socioeconomic status indices and control variables, and longitudinally at T2, controlling for T1 executive function. *N* for all models = 2,726.

The predictor variables for my analyses were the following indices of socioeconomic status: highest parental occupation (0−8), how many of the pupil's parents attended university (0, 1, or 2), area-level deprivation (1−5), and Free School Meals status (0, 1). I controlled for age, self-reported gender (male/female), ethnicity (white/black/Asian/mixed), and first language status (English learnt first/English learnt at the same time as another language/English not the first language learnt). Dummy variables were created for ethnicity and first language status, with the most common categories (white and English learnt first) used as the reference categories. I included age as executive function skills continue to improve during adolescence (Huizinga et al., 2006), gender as it may predict different cognitive developmental trajectories (Grissom & Reyes, 2019), ethnicity as it associates with socioeconomic status in the UK (GOV.UK, 2018) and differences in executive function skills in other studies (Rea-Sandin et al., 2021), and first language status as it associates with executive function skills and socioeconomic status (Engel de Abreu et al., 2012; Filippi et al., 2022).

To test for generality versus specificity of associations, I ran three types of models. For the first, general associations model, T1 socioeconomic status, and T1 executive function

and T2 executive function factors were created using confirmatory factor analysis (CFA), using the four socioeconomic status indices and five executive function measures: TMT switch cost, BDS span, Corsi span, SWM errors and CPT errors, respectively (SWM strategy, which is less commonly used, was not included to avoid issues of multicollinearity). Similar analyses were carried out on language ability and non-verbal reasoning as outcome variables for comparison.

Specific associations models then included either the socioeconomic status factor as a predictor of performance on individual executive function measures or individual socioeconomic status indices as predictors of the executive function factor. In a final set of exploratory analyses, models were ran where individual socioeconomic status indices were entered as predictors of performance on individual executive function measures. Due to its relatively low sample size, to run the final type of model with AX-CPT errors as an outcome I collapsed some categories for parent occupation (8 categories collapsed into 4) and area deprivation (levels 1 and 2) such that all categories contained >30 participants with data on the AX-CPT.

Cross-sectional analyses investigated associations between socioeconomic status indices and executive function measures at T1. Control variables were entered in a first block, and the socioeconomic status measure(s) in a second block. As a sensitivity check, cross-sectional analyses were rerun including state school participants who were present at T1 but not T2 testing and these showed a similar pattern of results (**Chapter 3 Appendices: Appendix A**). Longitudinal analyses assessed associations with socioeconomic status that may occur in early to mid-adolescence, controlling for the association between socioeconomic status and cognition in childhood by including the T1 factor/measure for the task in question in the regression equation. T2 executive function outcome measures were entered as the dependent variables, and lag time between measurement points and the

corresponding T1 executive function outcome measure were entered as additional predictors in block 1.

As a robustness check, I reran models 1-3 adding the auxiliary variables school type (dummy coded: community versus academy, foundation/voluntary versus academy), duration of testing session (continuous), and percentage of pupils in the school on Free School Meals (continuous) using the saturated correlates approach (Graham, 2003). Results are reported in section **3.3.3** and **Chapter 3 Appendices D** and **E**.

3.2.2 Other cognitive measures

I repeated my first model with language skills and non-verbal reasoning as outcomes. I used participants' average score across reading and writing at age 11 as my measure of language skills. Reading scores were multiplied by 4 and writing scores by 3 prior to averaging to put them on the same scale.

Stimuli from the Cattel's Culture Fair Test (CFT; Cattell et al., 1960) Form A, Scale 2 as a measure of non-verbal reasoning, specifically the Odd One Out and Complete the Pattern subtests. In the Odd One Out task, participants had to select which image out of a series of five images did not match the other four. The Complete the Pattern task is very similar to the Raven's Progressive Matrices (Raven et al., 1998) and required participants to select which stimulus array (out of five) completed the pattern shown in the three filled squares of a 2 x 2 grid. Both subtasks started with an animated demonstration of a single trial and were followed by a practice trial, with feedback, which the participant could not progress from until the correct answer was chosen. Participants then had three minutes for each task to complete as many trials as possible (up to 14 for Odd One Out; up to 11 for Complete the Pattern). The trials were shown in increasing order of difficulty. Failing four out of five items in a row resulted in the subtask being terminated early, as this indicated chance performance.

Participants were still allowed to proceed to the Complete the Pattern task in the instance that the Odd One Out task was terminated early.

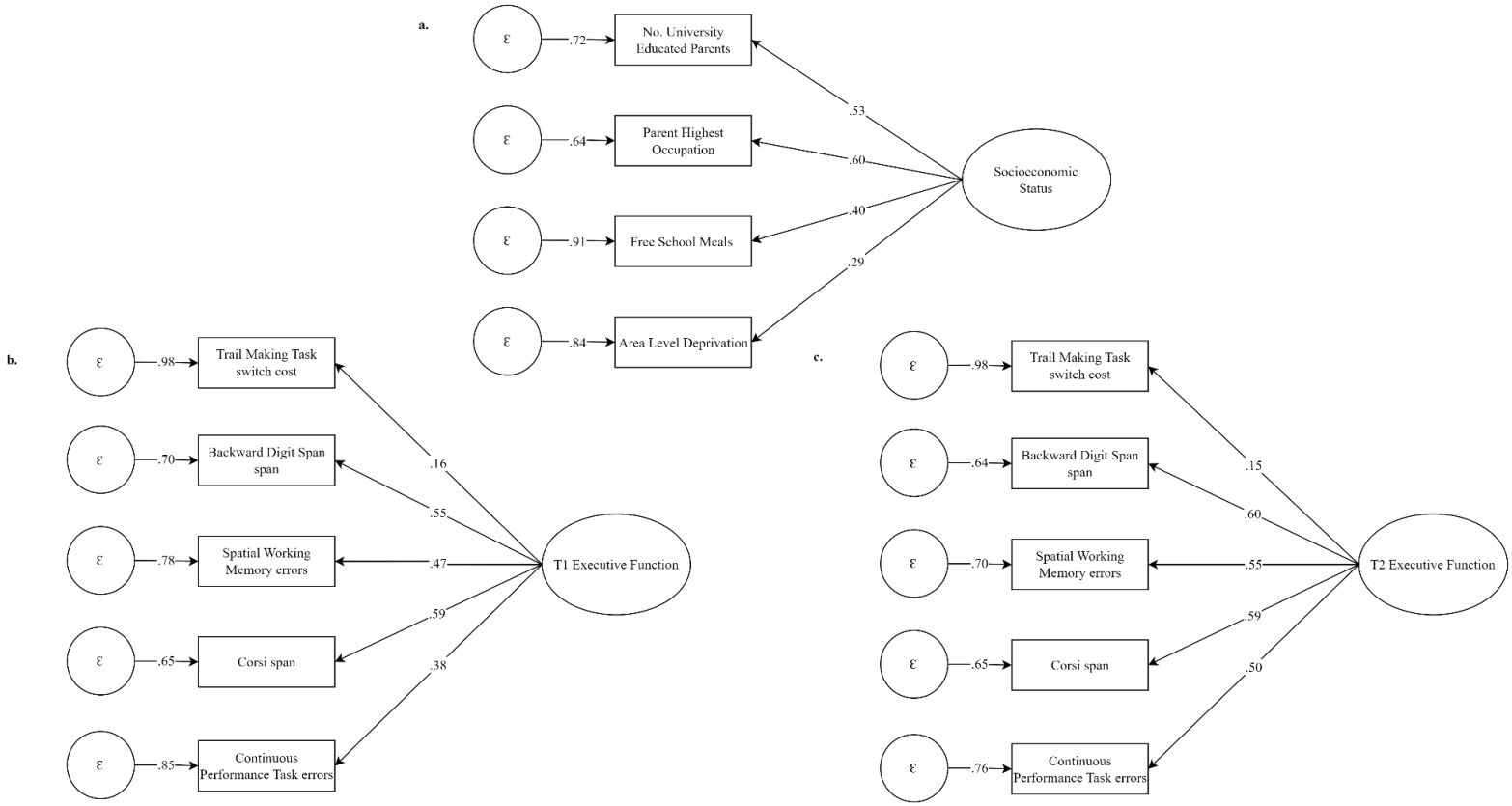
3.2.3 Confirmatory Factor Analysis

CFAs were carried out to construct a T1 socioeconomic status factor and executive function latent factors at T1 and T2. Robust fit estimates were acceptable for a one factor model of socioeconomic status factor (CFI = 0.96, RMSEA = 0.07) and one factor models of executive function at T1 (CFI = 1.00, RMSEA = 0.00) and T2 (CFI = 1.00, RMSEA = 0.01). All loadings were significant at $p < .001$ (**Figure 3.1**). Models were very similar, but there was a slight increase in factor loadings at T2 for all executive function measures except the TMT switch cost. The executive function CFAs were rerun excluding CPT errors as I was concerned about the small number of participants with data for this measure. Fit indices showed very little difference between these models at T1 and superior fit for the factor including CPT errors at T2 (T1 $CFI_{no\ CPT} = 1.00$; $RMSEA_{no\ CPT} = 0.00$; T1 $CFI_{no\ CPT} = 0.99$; $RMSEA_{no\ CPT} = .04$), so I decided to include this measure in the factor.

The loading of TMT switch onto the executive function factor was quite weak at both timepoints. All other loadings were at least moderately strong following Tavakol and Wetzel (2020), with the working memory measures contributing more to the latent factor. For the socioeconomic status factor, area deprivation and Free School Meals contributed less strongly to the latent factor than parental occupation and education although both loadings were moderate or close to moderate. The former is likely to have less commonality with the other socioeconomic status indices as it is not a family level measure and the latter likely loaded poorly because it picks up on the family composition i.e., whether pupils are living in single parent households.

Figure 3.1

Path diagrams showing the loadings of socioeconomic status and executive function measures on latent factors.



Note. Area deprivation and Free School Meals were reverse coded for factor analysis so that a higher score reflects higher socioeconomic status. For tasks where a higher score reflects worse performance (TMT switch, SWM errors and CPT errors), scores were also reversed.

3.3 Results

3.3.1 Descriptives

Table 3.1 shows the average scores on each measure at T1 and at T2. Paired T-tests using pairwise complete selection indicated that pupils performed significantly better on all executive function measures and non-verbal reasoning at T2. T1 and T2 measures on each task showed positive parametric correlations that were mostly above .30, except for the TMT switch cost and SWM strategy measures, suggesting these two measures may be less reliable.

Table 3.1

Average scores on the executive function tasks and comparison measures at T1 and T2.

	***n* T1**	**T1 *M (SD)***	***n* T2**	**T2 *M (SD)***	***n* T1 & T2**	**% change T1-T2[a]**	**T1-T2 *r*[b]**
TMT switch cost	2,636	1.83 (0.58)	2,573	1.79 (0.56)	2,493	-2.7%***	.22***
BDS	2,503	4.02 (0.86)	2,604	4.33 (0.96)	2,416	7.5%***	.50***
SWM errors	2,616	29.19 (13.15)	2,425	26.35 (12.66)	2,339	-10.11%***	.34***
SWM strategy	2,619	10.71 (2.82)	2,431	10.34 (2.89)	2,345	-3.5%***	.18***
Corsi span	1,584	4.93 (0.75)	979	5.20 (0.89)	747	6.1%***	.49***
CPT errors	586	5.07 (5.10)	351	4.22 (5.04)	159	-28.80%***	.34***
CFT score	2,451	13.16 (3.63)	2,489	14.23 (3.63)	2,254	8.9%***	.49***
Language SAT score	2,558	4.35 (0.67)			N/A		

Note. TMT = Trail Making Task; BDS = Backwards Digit Span; SWM = Spatial Working Memory; CPT = Continuous Performance Task; CFT = Culture Fair Test. For CFT, BDS, and Corsi, a higher score = better performance. For TMT switch cost, SWM errors, SWM strategy, CPT errors, a higher score = worse performance. [a] T-tests were carried out to compare T1 and T2 performance for participants with longitudinal data. [b] Pearson correlations were carried out between T1 and T2 data. ** $p < .05$, ** $p < .01$, *** $p < .001$.*

3.3.2 Correlation analyses

Table 3.2 shows the cross-sectional correlations between all the variables of interest at T1, while **Table 3.3** shows the longitudinal correlations between T1 predictors/controls and T2 outcome variables. Correlations were run using pairwise complete selection. Dummy variables were created for ethnicity and first language and their associations with the key socioeconomic status and executive function measures are presented in **Chapter 3 Appendices**: **Appendix B** and **C**.

The strongest correlations tended to be between socioeconomic status measures, and between executive function measures, although associations of TMT switch with other executive function measures were weak. All socioeconomic status indices other than parental education level significantly associated with multiple executive function measures. BDS, SWM errors, Corsi span and CPT errors had the largest correlations with socioeconomic status. CFT and language had slightly stronger correlations with socioeconomic status than did most of the executive function measures. The pattern of associations was similar cross-sectionally and longitudinally.

Table 3.2

Correlation matrix for the demographic, socioeconomic status, and cognitive measures at T1.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. T1 Gender															
2. T1 Age	.00														
3. Parent education	**-.08**	-.04	***SES – SES associations***												
4. T1 Parent occupation	**-.04**	.02	**.34**												
5. T1 Area deprivation	**.11**	.00	**-.17**	**-.23**											
6. T1 Free School Meals	-.02	.02	**-.14**	**-.13**	**.18**										
7. T1 SES.f	**-.08**	-.01	**.72**	**.83**	**-.56**	**-.42**									
8. T1 CFT score	**.03**	**.08**	**.12**	**.11**	**-.11**	**-.10**	**.16**								
9. KS2 language†	**.10**	**.08**	**.11**	**.19**	**-.09**	**-.11**	**.19**	**.36**							
10. T1 TMT switch	-.01	.02	-.04	.00	.03	.02	-.02	**-.07**	**.04**	***EF – EF associations***					
11. T1 BDS span	**.07**	.03	**.06**	**.06**	-.02	**-.05**	**.07**	**.36**	**.36**	**-.08**					
12. T1 SWM errors	**-.07**	-.03	-.02	**-.05**	**.07**	**.05**	**-.07**	**-.26**	**-.25**	**.07**	**-.26**				
13. T1 SWM strategy	.01	.01	-.02	-.04	.03	.02	-.04	**-.15**	**-.11**	.04	**-.12**	**.55**			
14. T1 Corsi span	.02	**.05**	.02	.05	-.01	**-.06**	.05	**.28**	**.27**	**-.11**	**.32**	**-.27**	**-.20**		
15. T1 CPT errors	-.01	-.04	-.05	**-.11**	**.10**	.00	**-.11**	**-.14**	**-.18**	**.09**	**-.16**	**.16**	**.13**	**-.21**	
16. T1 EF.f	**.07**	**.04**	**.05**	**.08**	**-.06**	**-.07**	**.09**	**.40**	**.36**	**-.22**	**.77**	**-.67**	**-.37**	**.79**	**-.50**

Note. Emboldened correlations are significant at $p < .05$. f signifies factors. SES = socioeconomic status; TMT = Trail Making Task; BDS = Backwards Digit Span; SWM = Spatial Working Memory; CPT = Continuous Performance Task; EF = executive function. For BDS and Corsi, a higher score = better performance. For TMT switch cost, SWM errors, SWM strategy and CPT errors, a higher score = worse performance. Gender is coded as female = 1. †This measure was collected in the year prior to T1.

Table 3.3

Correlation matrix for associations between T1 demographic and socioeconomic status measures and T2 cognitive measures.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. T1 Gender															
2. T1 Age	.00														
3. T1-T2 Lag time	**-.05**	**-.27**													
4. Parent education	**-.08**	-.04	**-.07**	*SES – SES associations*											
5. T1 Parent occupation	**-.04**	.02	**-.06**	**.34**											
6. T1 Area deprivation	**.11**	.00	**.21**	**-.17**	**-.23**										
7. T1 Free School Meals	-.02	.02	**.12**	**-.14**	**-.13**	**.18**									
8. T1 SES.f	**-.08**	-.01	**-.15**	**.72**	**.83**	**-.56**	**-.42**								
9. T2 CFT score	**.05**	**.09**	-.01	**.10**	**.14**	**-.10**	**-.12**	**.17**							
10. T2 TMT switch	.00	-.02	.02	.01	.00	.06	.01	-.02	**-.06**	*EF – EF associations*					
11. T2 BDS span	**.08**	.03	**.06**	**.06**	**.08**	-.02	**-.08**	**.09**	**.38**	**-.10**					
12. T2 SWM errors	**-.09**	-.02	-.01	.00	**-.05**	**.05**	**.06**	**-.06**	**-.28**	**.05**	**-.32**				
13. T2 SWM strategy	.03	**-.05**	-.01	-.01	-.03	.00	.02	-.03	**-.17**	**.02**	**-.19**	**.58**			
14. T2 Corsi span	.06	.06	.05	.00	.10	-.04	-.04	**.07**	**.31**	**-.13**	**.34**	**-.34**	**-.19**		
15. T2 CPT errors	-.07	-.08	-.06	-.05	-.09	-.03	-.06	-.04	**-.30**	**.07**	**-.30**	**.19**	**.14**	**-.25**	
16. T2 EF.f	**.10**	**.04**	**.05**	.04	**.10**	**-.05**	**-.08**	**.10**	**.42**	**-.20**	**.82**	**-.75**	**-.43**	**.76**	**-.61**

Note. Emboldened correlations are significant at $p < .05$. f signifies factors. SES = socioeconomic status; TMT = Trail Making Task; BDS = Backwards Digit Span; SWM = Spatial Working Memory; CPT = Continuous Performance Task; EF = executive function. For BDS and Corsi, a higher score = better performance. For TMT switch cost, SWM errors, SWM strategy and CPT errors, a higher score = worse performance. Gender is coded as female = 1. †This measure was collected in the year prior to T1.

3.3.3 Model 1. Testing for general effects of socioeconomic status on executive function

Model 1 was run to test the predictions that socioeconomic status, measured at age 12, would predict age 12 executive function (H1) and age 14 executive function, controlling for age 12 executive function (H2). Socioeconomic status explained 1% of additional variance in the T1 executive function factor after accounting for demographic controls and the T1 socioeconomic status factor had a small but significant positive association with the T1 executive function factor ($\beta = .11$, $p < .001$). Longitudinally, the socioeconomic status factor again explained an additional 1% of variance after controls and had a small but significant association with change in the executive function factor from T1 to T2 ($\beta = .07$, $p < .001$). These associations translate into an effect the size of a 2 IQ point increase per SD increase in socioeconomic status cross-sectionally and a 1 IQ point increase longitudinally (**Table 3.4** gives the full model parameter estimates). Socioeconomic status effects were slightly smaller - equivalent to a 1 IQ point change cross-sectionally ($\beta = .07$, $p < .001$) and three quarters of an IQ point longitudinally ($\beta = .05$, $p < .005$) – when auxiliary variables were added. These results are consistent with H1 and H2 and, in practice, mean that the socioeconomic status linked gradient in executive function skills increased slightly over adolescence. This is illustrated in **Figure 3.2**.

Table 3.4

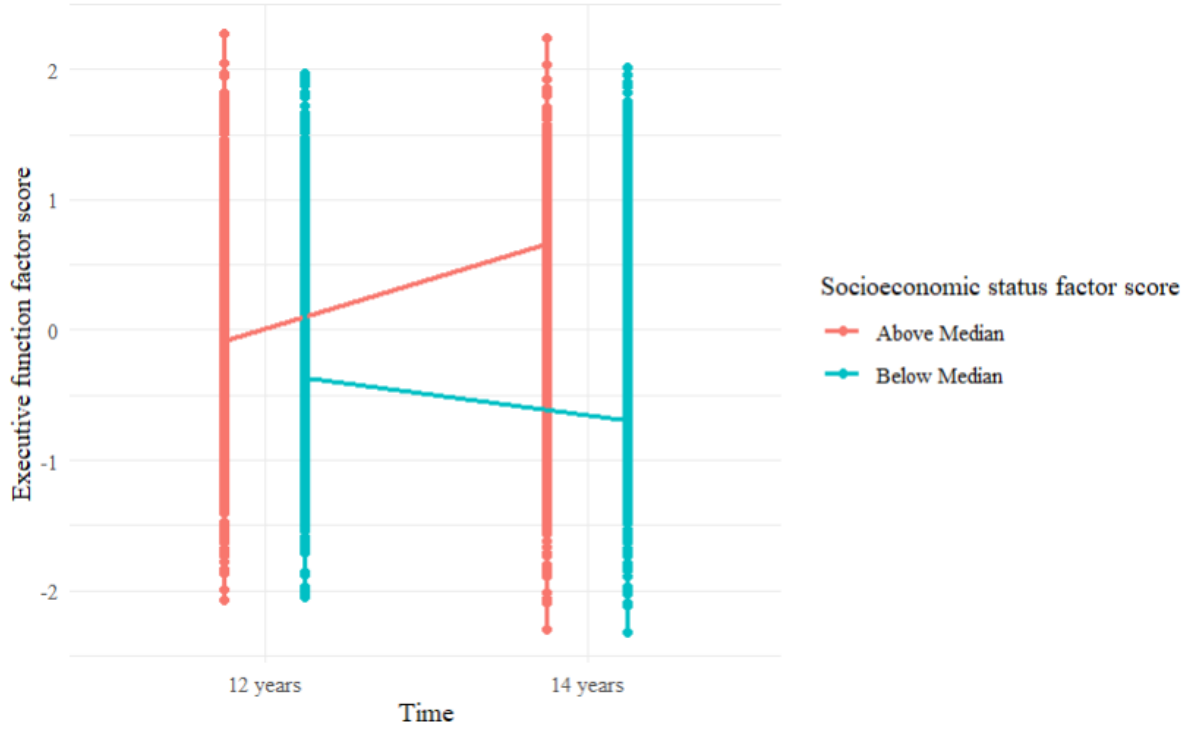
Standardised and unstandardised parameter estimates of control predictor variables for the cross-sectional and longitudinal general effects (executive function factor – socioeconomic status factor) models.

	Cross-sectional models		**Longitudinal models**	
	Standardised β [95% CI]	**Raw β [95% CI]**	**Standardised β [95% CI]**	**Raw β [95% CI]**
Age	.05 [.01, .09]*	0.09 [0.02, 0.16]	.03 [-.01, .06]	0.05 [-0.01, 0.11]
Female	.07 [.04, .11]***	0.11 [0.05, 0.16]	.06 [.03, .09]***	0.09 [0.05, 0.14]
Black	-.12 [-.16, -.08]***	-0.21 [-0.29, -.014]	-.05 [-.09, -.02]**	-0.10 [-0.16, -0.03]
Asian	.09 [.04, .13]***	0.13 [0.06, 0.20]	.02 [-.02, .06]	0.04 [-0.03, 0.10]
Mixed	.02 [-.02, .06]	0.05 [-0.04, .014]	.00 [-.04, .04]	0.00 [-0.08, 0.08]
Bilingual from birth	.02 [-.02, .06]	0.03 [-0.04, 0.09]	.03 [-.01, .06]	0.05 [-0.01, 0.10]
English not first language	-.06 [-.10, -.02]**	-0.11 [-0.17, -0.04]	.00 [-.03, .03]	0.00 [-0.06, 0.06]
Lag time	N/A		.05 [.01, .08]**	0.08 [0.02, 0.14]
T1 executive function factor			.53 [.51, .56]***	0.55 [0.52, 0.58]
Socioeconomic status factor	.11 [.07, .15]***	0.11 [0.07, 0.15]	.07 [.04, .11]***	0.08 [0.04, 0.11]
Full model R^2	.05		.33	

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

Figure 3.2

Graph showing a widening gap in executive function factor scores between pupils above and below the median score on the socioeconomic status factor from 12-14 years.



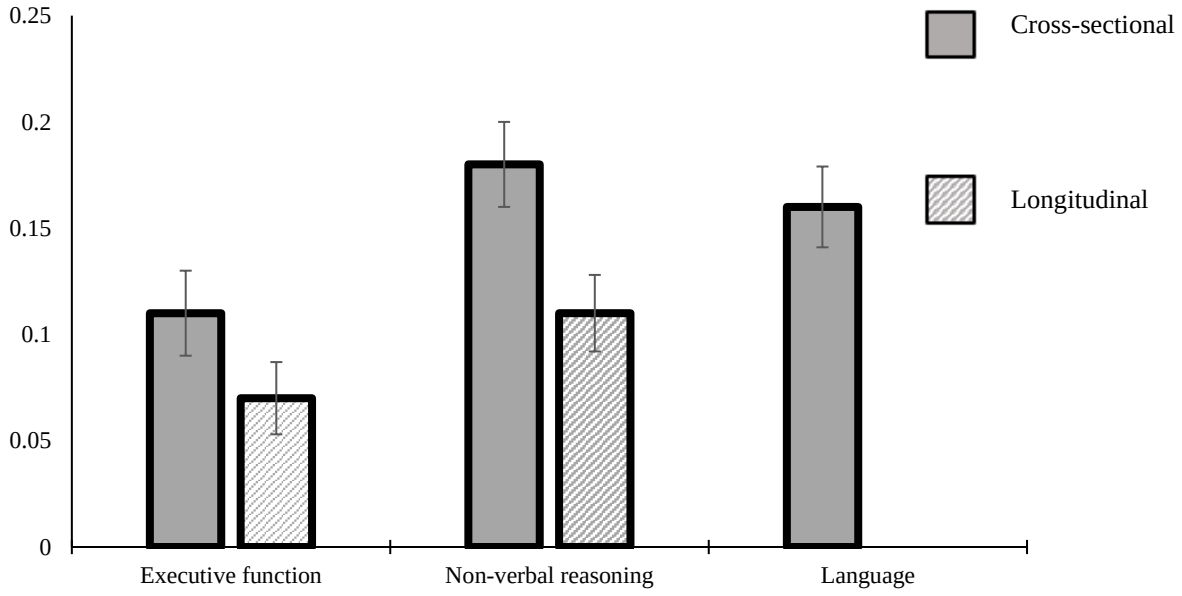
Note. A median split was used in this diagram for ease of the reader's interpretation, but the socioeconomic status factor was treated as a continuous predictor in the models. Dots are individual data points, and the lines intersect the stacked dots at the mean executive function for that group of participants.

For comparison, the same models were run with non-verbal reasoning and language SAT scores as outcome variables to explore the extent to which they were associated with socioeconomic status compared to executive function. The socioeconomic status factor explained 3% of the variance in T1 non-verbal reasoning after relevant controls and 4% in average language SAT score. Longitudinally, 1% of additional variance in T2 non-verbal reasoning was explained. **Figure 3.3** shows that cross-sectional associations between the socioeconomic status factor and non-verbal reasoning/language were around 1.5 times larger than the associations between the socioeconomic status factor and executive function; the longitudinal socioeconomic status factor to non-verbal reasoning association was also

stronger than the socioeconomic status-executive function association, although this difference was not as pronounced.

Figure 3.3

Bar graph showing beta estimates for the associations between T1 socioeconomic status factor and executive function factor and non-verbal reasoning scores cross-sectionally (T1) and longitudinally (T2, controlling for T1), and between T1 socioeconomic status and age 11 language scores.



Notes. Error bars show SE of the estimates. Emboldened bars are significant betas at $p < .05$.

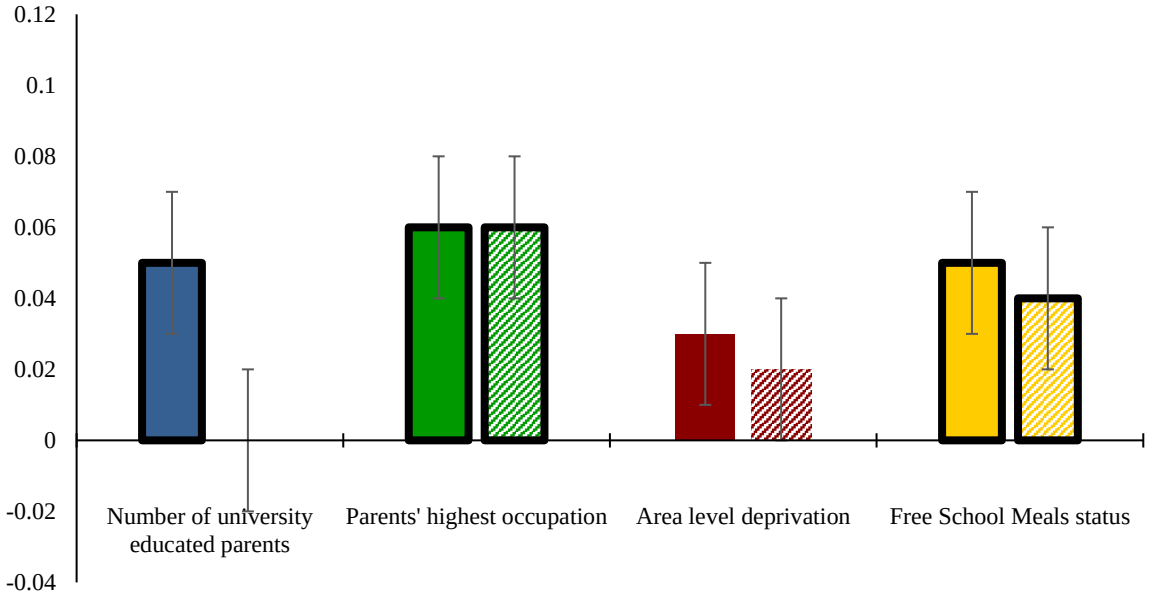
3.3.4 Model 2. Testing for differential relations between socioeconomic status indices and executive function

Model 2 tested the prediction that there would be some specificity of socioeconomic status to executive function relationships at the socioeconomic status indicator level (H3). The percentage of variance explained in executive function composite score by socioeconomic status was unchanged when I treated the socioeconomic status indices as

individual predictors rather than a factor. **Figure 3.4** and **Table 3.5** gives the beta estimates for the associations between the different socioeconomic status indices and T1 executive function or change in executive function from T1-T2. These show the effect of a 1 SD increase in the socioeconomic status indices on the executive function factor or on change in the executive function factor.

Figure 3.4

Bar graph showing the beta estimates for the relationships between the four socioeconomic status indices and the general executive function factor cross-sectionally (T1, filled bars) and longitudinally (T2, controlling for T1, hashed bars).



Note. Error bars show *SE*. Emboldened bars are significant betas at $p < .05$. Betas were reversed for ease of interpretation – higher betas indicate that better executive function performance is associated with higher socioeconomic status.

Table 3.5

Parameter estimates for each socioeconomic status index entered in the multiple regressions predicting the executive function factor at T1 (cross-sectional model) and T2 controlling for T1 (longitudinal model).

Predictor	**Cross-sectional**		**Longitudinal**	
	Standardised β [CIs]	**Raw β [CIs]**	**Standardised β (CIs)**	**Raw β (CIs)**
Parental education	.05 [.00, .10]*	0.04 [0.00, 0.08]	.00 (-.04, .04)	0.00 (-0.03, 0.04)
Highest occupation	.06 [.02, .11]**	0.02 [0.01, 0.04]	.06 (.02, .10)**	0.02 (0.01, 0.04)
Area level deprivation	-.03 [-.07, .01]	-0.02 [-0.04, 0.01]	-.02 (-.06, .01)	-0.01 (-0.03, 0.01)
Free School Meals	-.05 [-.09, -.01]*	-0.09 [-0.16, -0.02]	-.04 (-.07, -.01)*	-0.07 (-0.13, -0.01)
Full model R^2	.05		.33	

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

Cross-sectionally, all socioeconomic status indices other than area level deprivation significantly predicted unique variance in T1 executive function. However, only parental occupation and FSM status were significantly associated with the change in executive function over adolescence in longitudinal models. All socioeconomic status effects were small. This remained true when auxiliary variables were added, with only slight attenuation in effect size estimates (see **Chapter 3 Appendices: Appendix D**). H3 was thus supported, with greater evidence for specificity in the longitudinal model.

3.3.5 Model 3. Testing sensitivity of different executive function measures to socioeconomic status

Model 3 was the inverse of model 2, with individual socioeconomic status predictors and an executive function factor. It was designed to test the prediction (H4) that socioeconomic status to executive function associations would be specific to certain executive function measures.

After accounting for demographic controls, socioeconomic status explained an additional 1% of the variance in AX-CPT errors cross-sectionally at T1. Further, an additional 1% of the change in BDS, Corsi span and of AX-CPT errors over adolescence was explained by the socioeconomic status factor after controlling for demographic characteristics (see **Table 3.6** for the full model R^2 values). No additional variance in other executive function measures was explained by socioeconomic status. Cross-sectionally, there was limited specificity in the relationships between the socioeconomic status factor and different executive function measures; all executive function measures other than TMT switch cost were significantly associated with socioeconomic status (**Table 3.6** and **Figure 3.5**). This remained true after false discovery rate (FDR) correction across the six comparisons. The BDS, SWM errors and AX-CPT errors effects also remained significant with the addition of auxiliary variables, despite attenuations in the sizes of the first two associations, and the Corsi effect approached significance (p = .054, **Chapter 3 Appendices: Appendix E**). However, longitudinally socioeconomic status was only related to change in performance on the working memory tasks (**Figure 3.5**). The socioeconomic status-working memory span associations remained significant after FDR correction but not the association of socioeconomic status with SWM errors. The longitudinal span task associations also remained significant with the addition of auxiliary variables (**Chapter 3 Appendices: Appendix E**), although effect sizes were reduced by around a third. These findings are consistent with H4 with, again, greater evidence for specificity in the longitudinal model.

Table 3.6

Parameter estimates for T1 socioeconomic status factor associations with different executive function measures and variance explained by the whole models. Beta values describe the

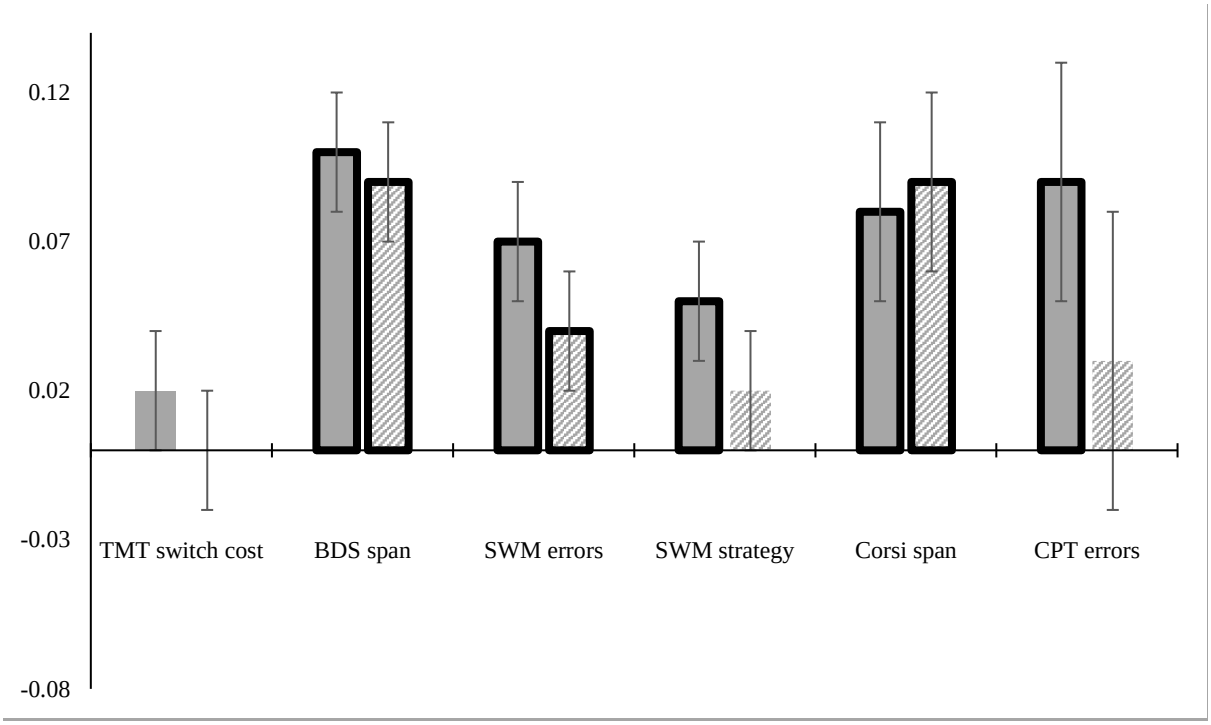
effect of a 1 SD increase in the socioeconomic status factor on different executive function measures.

	Cross-sectional models			Longitudinal models		
	Standardised β [CIs]	**Raw β [CIs]**	R^2	**Standardised β [CIs]**	**Raw β [CIs]**	R^2
TMT switch	-.02 [-.05, .03]	-0.01 [-0.05, 0.02]	.01	.00 [-.04, .04]	0.00 [-0.04, 0.03]	.06
BDS span	**.10 [.06, .14]*****	**0.12 [0.07, 0.17]**	.03	**.09 [.05, .12]*****	**0.12 [0.07, 0.16]**	.28
SWM errors	**-.07 [-.11, -.03]*****	**-1.35 [-2.08, -0.62]**	.03	-.04 [-.08, .00]*	**-0.74 [-1.45, -0.04]**	.13
SWM strategy	**-.05 [-.09, -.01]***	**-0.18 [-0.34, -0.02]**	.01	-.02 [-.06, .02]	-0.08 [-0.06, 0.02]	.04
Corsi span	**.08 [.03, .15]****	**0.08 [0.03, 0.13]**	.04	**.09 [.03, .15]****	0.11 [0.04, 0.19]	.26
CPT errors	**-.09 [-.17, -.01]***	**-0.64 [-1.25, -0.04]**	.02	-.03 [-.13, .08]	-0.20 [-0.94, 0.54]	.20

Note. TMT = Trail Making Task; BDS = Backwards Digit Span; SWM = Spatial Working Memory; CPT = Continuous Performance Task. Significant betas after FDR correction (*p*-value thresholds corrected for 6 comparisons cross-sectionally and 6 longitudinally) are emboldened.

Figure 3.5

Bar graph showing the beta estimates for the relationships between the T1 socioeconomic status factor and different executive function measures cross-sectionally (T1, filled bars) and longitudinally (T2, controlling for T1, hashed bars).



Note. TMT = Trail Making Task; BDS = Backwards Digit Span; SWM = Spatial Working Memory; CPT = Continuous Performance Task. For tasks where higher score = worse performance, betas were reversed before plotting for ease of interpretation, therefore higher betas indicate that higher executive function performance is associated with higher socioeconomic status. Error bars show SE of the estimates. Emboldened bars are significant betas at $p < .05$.

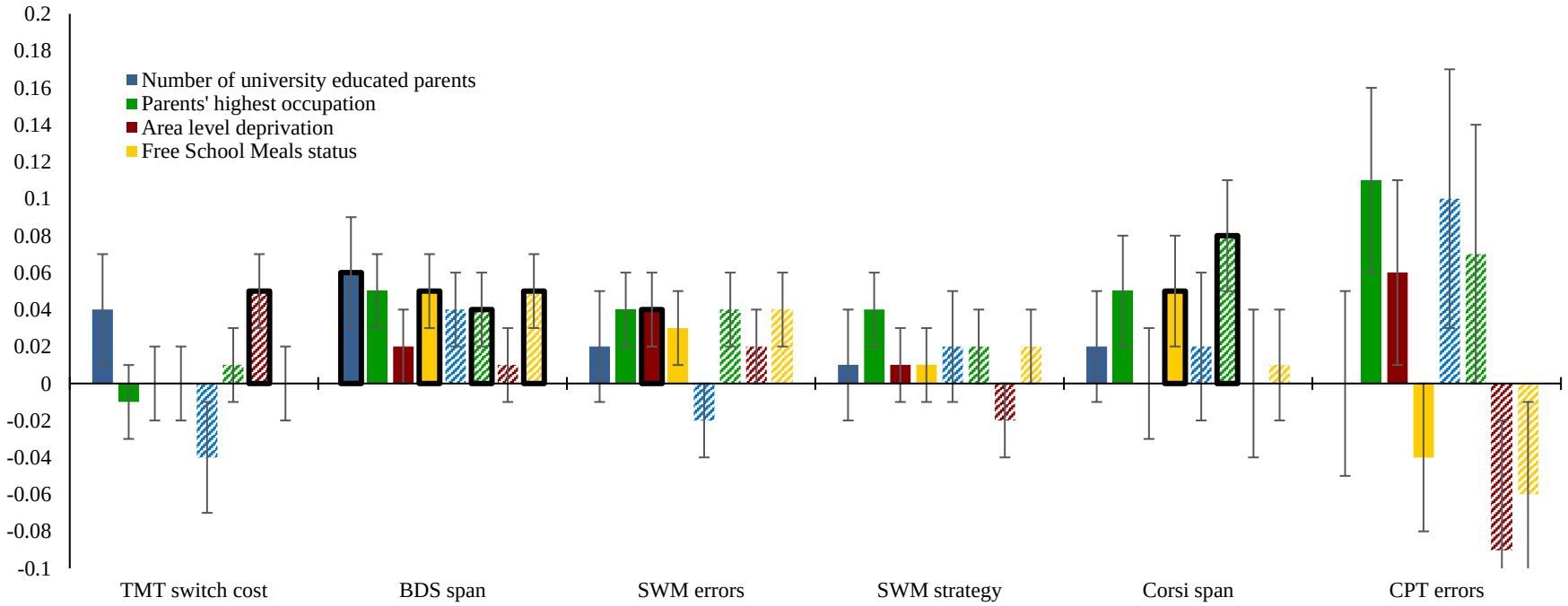
3.3.6 Model 4. Associations of individual socioeconomic status indices with performance on individual executive function measures

As supplementary analysis, I further tested for specificity of associations by looking at individual socioeconomic status indices as predictors of performance on individual

executive function measures (**Figure 3.6**). These were low-powered tests; no associations were significant after FDR correction for 24 comparisons (4 socioeconomic status indices x 6 executive function measures) cross-sectionally or longitudinally. However, they reveal a pattern of results that complement the first set of analyses; namely that parent occupation and FSM status were the most reliable socioeconomic status predictors and that the BDS and Corsi were particularly sensitive to these aspects of socioeconomic status. Additional specific associations were observed, notably with area deprivation, but these should be interpreted with caution.

Figure 3.6

Bar graph showing the beta coefficients of the associations between individual socioeconomic status indices and individual executive function measures cross-sectionally (filled) and longitudinally (hashed).



Note. TMT = Trail Making Task; BDS = Backwards Digit Span; SWM = Spatial Working Memory; CPT = Continuous Performance Task. For tasks where higher score = worse performance, betas were reversed before plotting for ease of interpretation, so positive betas reflect higher executive function scores associate with higher socioeconomic status. Error bars show SE of the estimates. Emboldened bars are significant betas at $p < .05$.

3.4 Discussion

3.4.1 Results summary

This study explored the nature of associations between socioeconomic status and executive function in a large longitudinal dataset with cognitive measures from early to mid-adolescence. I was interested in assessing the extent to which socioeconomic status may associate with the development of executive function during adolescence, beyond the associations reported in childhood, and in investigating the specificity of associations between socioeconomic status and executive function. I assessed how a range of socioeconomic status indices (parental education level, parental occupation, area level deprivation and Free School Meals status) were related to performance on a switching task (TMT), a measure of verbal working memory (BDS), two spatial working memory tasks (SWM and Corsi) and a measure of sustained attention/inhibitory control (CPT).

Combining socioeconomic status indices and executive function measures into latent factors, I first established that socioeconomic status was significantly associated with executive function at age 12 and that socioeconomic status predicted change in executive function skills from early to mid-adolescence. Though these relations were small (the beta values indicated changes equivalent to 2 IQ point increase per *SD* increase in socioeconomic status cross-sectionally and 1 longitudinally, or 1 IQ point and half an IQ point when auxiliary variables were added) in comparison to the associations of socioeconomic status with non-verbal reasoning and language ability[8], they are noteworthy as they indicate that socioeconomic status gaps in executive function widened over just a two-year period.

Looking at socioeconomic status indices as individual predictors of executive function, I observed a changing pattern of associations over adolescence. At age 12, all

[8] Although note that these measures are likely to involve executive function skills, just as executive function tasks may involve these other cognitive skills; these are not independent measures of distinct cognitive domains.

socioeconomic status indices (other than area deprivation) explained some unique variance in executive function, beyond common associations, however longitudinally only income and parental occupation were significant predictors of change in executive function skills. Likewise, models predicting performance on individual tasks from the socioeconomic status factor showed relatively non-discriminate associations with executive function measures at 12 years of age but specific associations with working memory span tasks over adolescence.

3.4.2 Consistency with the wider literature

Broadly, my findings are consistent with previous studies of adolescents which demonstrate significant cross-sectional (Fatima & Sheikh, 2014; Madhushanthi et al., 2020; Pluck et al., 2021, but also see Mance et al., 2019) and longitudinal (Sutin et al., 2022) associations between socioeconomic status and executive function. The effect sizes I observed fit with Lawson et al.'s (2018) meta-analysis of studies looking at socioeconomic status-executive function associations, predominantly in younger samples, which showed a small overall effect size of socioeconomic status on executive function. Importantly, Lawson et al. found that effect sizes tend to be larger (up to moderate in size) in more socioeconomically diverse samples. Since my sample was biased towards having highly educated parents, I may therefore have underestimated the relationship between this aspect of socioeconomic status and executive function.

Further, the effects reported in this study might underestimate the extent of socioeconomic status links to executive function for adolescents living outside of the capital. Research by the Institute for Fiscal Studies (Farquharson et al., 2022) shows that the attainment gap is significantly narrower in London compared to the rest of the UK, driven by pupils from low socioeconomic backgrounds attaining significantly higher grades than they would be expected to elsewhere in the country. One of the main reasons thought to explain this so-called London effect is school quality (Blanden et al., 2015). Given that positive

school climate has been shown to moderate the relationship between family income and executive function task performance, boosting the performance of the low-income pupils (Piccolo et al., 2016), then there may also be a London effect on executive function. If so, then social inequalities in executive function would be expected to be greater for adolescents residing in other areas of the UK.

Looking at socioeconomic status indices as individual predictors of executive function, I found some evidence of specificity as predicted, consistent with previous studies of adolescents (Madhushanthi et al., 2020; Sutin et al., 2022). However, the nature of these associations was somewhat different from previous research. Like Madhushanthi et al., I observed cross-sectional associations from parent education to executive function, but unlike them I also observed significant associations of executive function with occupation and income. The latter two associations were maintained longitudinally, and I found no evidence, contrary to Sutin et al., that area deprivation predicts executive function.

In Mashushanthi et al. (2020), the size of the association between parent occupation and adolescents' working memory was comparable to the cross-sectional occupation - executive function factor association in the present study[9]. However, the parental education associations with executive function measures in Madhushanthi et al. were up to three times larger than what I observed and the household income associations with executive function were almost zero in their sample. These differences may be explained by cultural factors, such as the degree of parental involvement in children's education during adolescence (e.g., see (Ekanayake et al., 2021; Pathirana, 2016). Since I employed a coarser measure of parental education (years in education), the previous study may have been also better able to detect linear relationships between this aspect of socioeconomic status and executive function.

[9] And larger than the effect of parent occupation on our individual working memory measures. Note that this association was not significant in Madhushanthi et al., likely due to their smaller sample.

Several studies have shown significant longitudinal relations between parental education level and executive function during childhood (Blair et al., 2011; Vrantsidis et al., 2020; Waters et al., 2021). It is therefore possible that the cross-sectional association I observed at T1 reflects the prior effects of factors related to parent education on executive function during childhood. The changing nature of parent-child and child-peer relationships that occurs during adolescence, which could mean that the mechanisms through which different socioeconomic status indices are related to cognitive development change, may go some way to explain this difference between the cross-sectional and longitudinal analysis. Longitudinal research is needed across the transitional period from primary to secondary education to explore this possibility, because, in my study, individual differences may be conflated with socioeconomic status-related effects due to the cross-sectional nature of the data. Note, though, that parental education levels may have been more varied in the countries in which the previous studies were conducted in.

In the present study, household poverty and parent occupation were related to widening gaps in executive function from early to mid-adolescence, whilst parental education and area deprivation were not. These results may reflect differences in the extent of exposure to cognitive stimulation as a result of socioeconomic status (Rosen et al., 2019). For example, in the UK, adolescents living in poverty have limited access to extracurricular activities positively associated with executive function – e.g., private tutoring (Zhang, 2018), playing musical instruments (Rodriguez-Gomez & Talero-Gutiérrez, 2022), and sports participation (Vasilopoulos et al., 2023) – and parents' occupation prestige may influence the extent to which they encourage participation in such activities to widen opportunities for their child. Another possible explanation of the occupation association is that the amount of time parents spend with the adolescent due to unsociable working hours (more common in low prestige jobs in the UK; Lyonette & Clark, 2009) negatively influences the degree of parental

supervision possible (Wight et al., 2008). This, in turn, could increase the likelihood of the adolescent engaging in risky health behaviours (See, 2016) known to negatively influence cognitive development.

Household poverty associations may also be explained by nutrition (e.g., Roberts et al., 2022) and, in the case of this study, the fact that our indicator tells us something about family composition. Because of the very low threshold for eligibility (equivalent to <1 adult full time minimum wage) pupils in receipt of free school meals are often from single parent families, something that none of my other measures were sensitive to. Previous research has shown that, amongst children from low socioeconomic status families, children from single parent families score lower on executive function measures than children from intact families (Sarsour et al., 2011). The associations of Free School Meals status with cognitive and academic outcomes reported here might therefore index the interaction between income and being raised in a single parent family.

Unlike income and occupation, in this study, area deprivation was not significantly related to executive function cross-sectionally or longitudinally. This finding is inconsistent with Sutin et al. (2022) who identified a longitudinal association of this index with cognitive skills in adolescents. The rapid redevelopment of historically poorer London neighbourhoods due to gentrification may have meant that my index based on 2011 census records may not be a valid account of relative deprivation in this study. It is possible that the pattern of area-level deprivation – executive function associations I observed might have been different if more up to date population statistics were available or had my area deprivation data been less skewed. I offer the only evidence, to my knowledge, of the relationship between area deprivation and change in executive function over adolescence, so further research into the importance of this predictor is needed.

I also offer evidence supporting the notion of differential susceptibility of different executive functions to socioeconomic status during adolescence. This finding fits with previous studies of adolescents (Madhushanthi et al., 2020; Sutin et al., 2022) and adults (Mittal et al., 2015; Young et al., 2018), but not children (Lawson et al., 2018), suggesting that differential relationships between socioeconomic status and different executive function measures may not be observable/emerge until this developmental period. This could be because of the lower reliability of individual executive function measures for children (Lawson et al., 2018), because of the increasing differentiation of executive function over adolescence (Karr et al., 2018; Lee et al., 2013) or because the effects of socioeconomic status related factors compound over time since they tend to remain stable during a young person's lifetime (Hackman et al., 2015).

In contrast to Lawson et al. (2018), I did not find that socioeconomic status associations with a general executive function factor were considerably larger than for specific socioeconomic status-executive function associations. Instead, the longitudinal relationships between socioeconomic status and the working memory span tasks were slightly larger than the longitudinal relations between socioeconomic status and the executive function factor. That I found that the working memory span tasks were particularly sensitive to socioeconomic status is consistent with previous studies comparing the associations between socioeconomic status and different executive functions (Donati et al., 2019; Lawson et al., 2018; Madhashanthi et al., 2020). The continued maturation of working memory skills and the systems which subserve them through adolescence (e.g., Finn et al., 2010; Ferguson et al., 2021; Lee et al., 2013) may make them relatively more vulnerable to the compounding effects of socioeconomic status over time than other executive functions. In support of this notion, differences in activation in fronto-parietal regions, thought to subserve working

memory, during a working memory (2-back) task based on socioeconomic status have been observed in adolescence elsewhere (Murtha et al., 2022).

By contrast, some evidence suggests that shifting may be a relative strength of individuals from disadvantaged backgrounds (Mittal et al., 2015). It has been suggested that it may be adaptive to quickly switch between task goals in the context of a chaotic and unpredictable home environment. Consistent with the idea that switching is a well-practiced skill in individuals from low socioeconomic status families, Mittal et al. found that adults who grew up in stressful home environments were faster on a switching task without any accuracy trade-offs. This may be why we observed a socioeconomic status gradient in switching neither cross-sectionally nor longitudinally.

Previous studies of children have shown associations between parental education and inhibitory control (e.g., Assari, 2020; Cabello et al., 2017) and that social inequalities in inhibition may be mediated by parental warmth and discipline (Xing et al., 2019). Xing et al. suggest that low socioeconomic status parents may experience emotional struggles and have a lack of quality time with their children, leading to harsher discipline and lower warmth toward their children. They suggest that this, in turn, may dissuade the development of the child's behavioural control as they are less intrinsically motivated and more distressed. That we found an effect of socioeconomic status on inhibitory control at 11 but not an effect on change in inhibitory control from 11-14 years suggests that any effects of socioeconomic status on inhibitory control may be established earlier and not persist through adolescence. Alternatively, our measure of parental education may have been too coarse to pick up on subtle individual differences in changes in inhibitory control over adolescence.

My findings regarding inhibitory control must be interpreted cautiously due to sample bias. Not all participants completed this task due to time constraints and previous work by the SCAMP team (unpublished) has shown that those who did were more likely to have

performed well on the earlier cognitive tasks. Further, because we did not use the typical outcomes from the AX-CPT due to data skewness it is difficult to compare the current findings to those from previous studies.

3.4.3 Strengths and limitations

A key strength of this study is that I was able to longitudinally study socioeconomic status-executive function associations in a large cohort. This made it possible to explore nuanced relationships and detect small, but possibly consequential increases in socioeconomic status-related gaps in executive function through adolescence. Previous studies (e.g., Rakesh et al., 2021; Rakesh et al., 2022; Tomlinson et al., 2020) have shown that the relationships between individual socioeconomic status indices and cognition and brain activity can change substantially once other socioeconomic status indices are controlled for. This is likely because different socioeconomic status indices explain overlapping variance in brain and cognitive development. Whilst it is true that the socioeconomic status indices I studied are highly related, the correlations between them are quite far from 1; it is possible to have highly educated parents on low incomes and vice versa, for example. Therefore, a key contribution of the current work is to reveal the extent to which individual facets of socioeconomic status explain an adolescent's cognitive skills when the rest of their sociodemographic background is considered. My findings provide a starting place from which further research can build to identify the mechanisms driving the observed associations. A better mechanistic understanding of socioeconomic status-executive function associations in this age group would allow for the design of targeted levelling up interventions.

Another limitation of this study is that I had multiple working memory measures but only one measure each for shifting (TMT switch cost) and inhibition (AX-CPT). This is important for several reasons. First, the shifting measure was not significantly related to

socioeconomic status in any model, suggesting it is relatively insensitive to socioeconomic status. However, the shifting measures showed a relatively low T1-T2 correlation, suggesting lower reliability. Shifting has rarely been studied in this context, so these results need replicating. Second, relatively few participants completed the inhibition measure, so I lacked statistical power to reliably assess associations between this measure and socioeconomic status. Those who did, were participants who had performed well in the initial tasks so some differences between results for different executive function measures may be due to sample differences. Future studies should replicate my models using a greater range of executive function measures.

A final limitation of this study is that I cannot rule out genetic effects that covary with socioeconomic status (e.g., see Allegrini et al., 2020), since I did not employ a genetically sensitive design. The interpretations offered assume environmentally mediated causal pathways, given my research aims.

3.4.4 Conclusions

This study provides the first evidence, to my knowledge, that socioeconomic status gaps in executive function widen during adolescence. Controlling for relevant demographic factors I found that associations between socioeconomic status and executive function were small but significant, nonetheless. At age 12, socioeconomic status associations were generally non-specific. However, longitudinal analyses showed that parental occupation and household poverty, but not parental education and area-level deprivation, predicted individual differences in executive function development. I also showed that socioeconomic status was specifically related to change in performance on working memory span tasks. These findings suggest that we should not only be concerned about social inequalities in cognitive development in the early years.

The associations observed in this study can only be fully understood with further study of mechanisms. Future work should attempt to identify proximal sources of the associations of parental occupation and income with developing executive function skills to inform theory and interventions aimed at mitigating social inequalities in cognitive development. Given the numerous associations between individual differences in executive function and adult life outcomes and the increase in socioeconomic status-related inequalities in executive function through adolescence reported here, the teenage years should be a higher research priority.

Chapter 4. The widening socioeconomic status gradient in attainment over adolescence is related to widening gaps in working memory skills

4.1 Introduction

In 2023, around 30% of UK pupils did not meet age expectations across subjects in their Key Stage 2 assessments (GOV.UK, 2023a) and a similar percentage of grades awarded at GCSE level were below the pass mark (Ofqual, 2023). Pupils from the most deprived neighbourhoods are around twice as likely to attain grades below the pass mark at GCSE level than pupils living in the richest neighbourhoods (Teach First, 2019). Beyond shaping the higher education and employment opportunities young people can access, school attainment negatively predicts an individual's likelihood of criminal convictions (Mõttus et al., 2012), suicide (Bjorkenstam et al., 2011), and age-related cognitive decline (Pudas & Rönnlund, 2019). Motivated by a need to mitigate the negative consequences of inequalities in academic achievement, researchers have identified a diverse range of social, psychological, and cognitive predictors of school success.

One large line of research spanning two decades, shows that executive function (executive function) skills predict educational attainment (e.g., see Jacob & Parkinson, 2015; Follmer, 2018 for reviews). However, from a meta-analysis of the literature, Jacob and Parkinson (2015, pp. 512) concluded that there was "no compelling evidence that a causal association between the two exists" and argued that all reported associations could be attributed to the covariance of executive function and attainment with socioeconomic status and prior attainment. This is an important consideration, given the substantial associations of socioeconomic status and prior attainment with subsequent attainment in the UK. In the UK pupils from the lowest income families are persistently nearly 30% less likely to achieve a pass at GCSE level (Tahir, 2022) and the average correlations between attainment at the end of primary school and end of secondary school are around $r = .50$ (Ofqual, 2014). Also, across studies, small to moderate associations between socioeconomic status and executive

function are observed (Lawson et al., 2018) and moderate associations between executive function and attainment are typically reported (Jacob & Parkinson, 2015).

Several subsequent studies have challenged Jacob and Parkinson's (2015) conclusion (Albert et al., 2020; Lawson & Farah, 2017; Waters et al., 2021), demonstrating that executive function is a robust predictor of school success over time, even when prior attainment and socioeconomic status are controlled for. Waters et al. showed that parental education predicted preschool attention, inhibition, and working memory, as well as first grade mathematics and reading achievement. Working memory was also a unique predictor of school outcomes and fully mediated the association between parent education and mathematics ability when controlling for academic and verbal ability assessed at baseline, as well as other child and family demographic factors. However, controlling for these factors there were no direct or indirect effects of income on attainment. Albert et al. and Lawson and Farah (2017) also explored the mediating role of executive function in longitudinal studies of the effects of socioeconomic status on changes in attainment. In these studies, their measures of socioeconomic status explained some unique variance in achievement and were not fully mediated by executive function.

Taken together, these findings show that executive function predicts some unique variance in academic ability for pupils of different socioeconomic status, and socioeconomic status predicts some unique variance in academic ability for pupils with different levels of executive function ability. These findings strongly suggest that executive function is not just a marker for socioeconomic status. Both socioeconomic status and executive function should hence be considered as important predictors in their own rights, as both contribute some unique explanatory power to understanding inequalities in academic achievement. However, the correlation between them needs to be accounted for.

It is noteworthy that Albert et al. (2020) and Lawson and Farah (2017) observed partial mediation, whilst Waters et al. (2021) observed full mediation, given that they looked at the same two socioeconomic status indices (parental education and income). The difference between these studies is that the former two employed a socioeconomic status composite, and the latter looked at these two aspects of socioeconomic status in separate models. It therefore seems that treating socioeconomic status indices as individual predictors of executive function and attainment can reveal nuanced effects which are masked by composite measures; the partial mediation of the socioeconomic status composites used by Albert et al. and Lawson and Farah may reflect the full mediation of parental education minus the non-mediation of household income observed by Waters et al. Adopting an approach to studying social inequality that embraces specificity is a positive step away from the typical deficit view of socioeconomic status impacts on the developing brain (e.g., see Frankenhuis & Nettle, 2020) and could help to inform tailored support for pupils at risk of academic difficulties. Nevertheless, since socioeconomic status indices tend to be significantly correlated, it is important to account for the associations between them when attempting to further delineate which indices predict executive and academic abilities.

The aforementioned studies (Albert et al., 2020; Lawson & Farah, 2017; Waters et al., 2021) also show that some executive function-attainment associations hold controlling for prior attainment. Importantly, findings from Ribner et al. (2017) suggest that executive function skills can moderate pupils' learning trajectories. They showed that, in students with limited mathematics knowledge at school entry, strong executive function skills enabled them to catch up by grade 5. This is suggestive of some effects of executive function on attainment independent of earlier attainment. Further, since Jacob and Parkinson's (2015) review, a number of significant positive associations between pre-school entry executive function and scholastic ability in primary school have been demonstrated when controlling for

socioeconomic status (e.g., Morgan et al., 2019; Morgan, Farkas, Hillemeier, et al., 2019; Nguyen & Duncan, 2019). Since studies measuring executive function before participants enter the school system find that executive function predicts how well students fare in later assessments, it seems that executive function is a valid predictor, not just a proxy for concurrent academic ability.

4.1.1 Social inequalities in executive function and attainment in adolescence

The literature reviewed above suggests that socioeconomic status, executive function, and prior attainment are likely to have some independent and some shared associations with academic attainment during primary education. However, since the majority of studies which look at relationships of executive function with socioeconomic status and school outcomes tend to involve children, it is unclear whether the same conclusion can be made for secondary education. Stipek and Valentino (2015) suggest that in early schooling executive function skills are key in enabling learning through instruction, but their importance declines as children develop factual and procedural knowledge that can be applied across subjects. This knowledge then becomes key in facilitating further learning.

Whilst there is evidence that the importance of subject specific knowledge for attainment grows over time (Lee & Bull, 2016) and that the importance of inhibitory control decreases (Cortés Pascual et al., 2019), subsequent studies of adolescents do not fully support Stipek and Valentino's (2015) prediction about the importance of executive function for attainment declining. Ahmed et al. (2021) have shown remarkable stability in executive function to attainment associations across development, providing a strong challenge to the Fade Out Hypothesis. In this study, adolescent (age 15) executive function was associated with adult attainment but explained no unique variance in attainment when preschool (age 5) executive function was accounted for. The authors suggest that this may be because the developmental changes in executive function are much more dramatic in early childhood.

Whilst this is true relative to age 15, early adolescence represents another rapid period of rapid cognitive development (e.g., Fuhrmann et al., 2015) so it is important to extend the study of executive function to attainment relationships in this age group.

Donati et al. (2019) made use of data from the Avon Longitudinal Study of Parents and Children (ALSPAC; http://www.bristol.ac.uk/alspac/), a longitudinal cohort study of children born in 1991-1992 in Southwest England. Using structural equation modelling, they showed that working memory, but not inhibitory control, measured at 11 predicted maths, science and English attainment at 16. Importantly, working memory explained significantly more variance in age 16 subject-specific attainment than attainment at age 11 and concurrent attainment in other subjects. This finding strongly refutes Stipek and Valentino's (2015) Fade out Hypothesis which suggests that executive function is only relevant for attainment in younger children. Studying the predictive ability of executive function measured at 5 for age 15 academic outcomes, whilst controlling for pre-school attainment, Ahmed et al. (2019) also found that working memory, but not other executive functions, continued to predict academic attainment during adolescence.

Donati et al. (2019) additionally showed that working memory - attainment associations held controlling for socioeconomic status, measured via parent occupation. They also found direct effects of parent occupation on attainment in maths, English and science but did not explore mediation of the socioeconomic status - attainment associations by working memory. Similarly, Ahmed et al. (2019) did not test whether working mediated socioeconomic status-attainment associations but showed that maternal education predicted measures of attainment but not measures of executive function at 15, whilst income predicted neither outcome at 15 years.

Indeed, only one study of adolescents has explored mediation of socioeconomic status associations with attainment. Albert et al. (2020) found that executive function (measured at

8-9 years) partially mediated the association of a composite measure of parental education and income with attainment in reading and maths at 13. This effect was strongest when working memory, and specifically verbal working memory, was the mediator compared to measures of planning or inhibition. In this study, verbal working memory explained 11% of the socioeconomic status effect on maths attainment and 7% of the effect on reading attainment. However, the authors did not control for prior attainment, so we cannot rule out the possibility that the covariance of working memory with attainment drove this effect.

The findings reviewed above suggest that, like in childhood, socioeconomic status, prior attainment, and executive function have some separable effects on attainment although the effects of executive function may be specific to working memory during this period. However, further research is needed to ascertain with confidence whether the Fade Out Hypothesis should be rejected, since only one two studies (Ahmed et al., 2019; Donati et al., 2019) have accounted for both socioeconomic status and prior attainment with this age group. More research looking at whether working memory mediates associations between socioeconomic status and change in attainment from childhood to adolescence is clearly needed, since there is evidence suggesting that inequalities in attainment widen during adolescence in the UK (Education Policy Institute, 2023), perhaps due to the cumulative effect of unchanging socioeconomic circumstances on cognitive development over many years (e.g., Hackman et al., 2015).

4.1.2 What is so special about working memory?

Contemporary theories of working memory view it as an active process that involves the short-term storage and manipulation of information in order to carry out a task at hand (e.g., Engle & Kane, 2004; Glavan & Houpt, 2019; Kovacs & Conway, 2019). The active part is generally thought to be executive attention, meaning that working memory involves both domain general and domain specific processes. Many learning exercises are multistep

and involve temporarily memorising whilst simultaneously manipulating information to successfully complete them. This may be one reason why working memory is so reliably related to attainment. Working memory is also a good match for the cognitive demands of secondary level assessment in the UK which involves a large amount of information being committed to memory, plus the active manipulation of this remembered information in order to apply it to an unseen exam question (see **Chapter 2** section **2.4.3**).

Importantly, working memory is the slowest developing executive function and continues to mature into the early 20s (Hartung et al., 2020). Working memory skills develop rapidly during early childhood and early adolescence, with relatively slower development in late childhood and adolescence (Ahmed et al., 2022). Several hierarchical theories suggest that more complex executive functions such as working memory are built upon simpler, earlier maturing systems such as inhibitory control and selective attention (e.g., Barkley, 1997; Bjorklund & Harnishfeger, 1990; Hendry et al., 2016). Since there is likely to therefore be greater individual variation in working memory compared to other executive functions during adolescence, this may explain why it predicts inter individual variability in attainment during adolescence and is not affected by *fade out* like other executive functions. The protracted developmental trajectory of working memory (Ferguson et al., 2021; Lee et al., 2013) may also explain the sensitivity of working memory to socioeconomic status during adolescence previously observed in this cohort (**Chapter 3**).

Just as there appears to be specificity at the level of executive function, the existing literature strongly suggests that there is likely to be specificity of associations at the subject level. In existing adolescent studies (Albert et al., 2020; Donati et al., 2019) and the literature on primary aged pupils (see Cortés Pascual et al., 2019 for a review), executive function has been shown to have stronger associations with attainment in maths than in literacy although these differences frequently do not reach statistical significance (e.g., see Jacob & Parkinson,

2015). Albert et al.'s findings suggest further nuance, whereby visuospatial working memory tasks are more predictive of maths attainment than English attainment.

4.1.3 Aims and hypotheses

This study aimed to replicate Donati et al. (2019) and Albert et al.'s findings (2020) regarding the specificity of associations between socioeconomic status, working memory and attainment during adolescence and the mediating role of working memory in the socioeconomic status-attainment association. I also wished to extend these previous studies by asking whether widening socioeconomic status related gaps in attainment during adolescence are attributable to widening socioeconomic status related gaps in working memory and by including a wider range of socioeconomic status measures.

I first predicted that socioeconomic status would significantly predict age 16 attainment, controlling for age 11 attainment (H1). I also expected that change in working memory skills over early to mid-adolescence would significantly predict later (age 16) attainment (H2). I anticipated that the effect of working memory on attainment would be stronger for maths and science than English (H3) given the subject specific associations between working memory and attainment reported elsewhere. I further expected that, treating working memory tasks separately, I would replicate Albert et al.'s (2020) findings that verbal working memory is a stronger predictor of attainment than visuospatial working memory (H4i) and that visuospatial working memory is more important for mathematics than English attainment (H4ii).

In the previous chapter I provided evidence that, in the SCAMP cohort, household poverty (indexed by Free School Meals status) and parental occupation are specifically related to widening gaps in executive function skills over adolescence holding other aspects of participants' socioeconomic circumstances constant. Hence, I predicted that only these indices would predict change in working memory but that all socioeconomic status indices

would predict attainment, given the associations between all indices and attainment in UK adolescents reported in previous studies (Chevalier et al., 2013; Donati et al., 2019; Mc Dool, 2017; Ermisch & Francesconi, 2001, H5).

Finally, I hypothesised that working memory would significantly mediate the association between socioeconomic status and change in attainment over adolescence (H6) and planned to test this in my best fitting model. As an exploratory step, I also controlled for Ofsted (Office for Standards in Education, Children's Services and Skills) rated school quality in the best fitting model. This was done to a) check that my results were not due to clustered sampling within schools and b) to isolate the effects of socioeconomic status on attainment from school quality effects on attainment, since school quality might covary with socioeconomic status,

4.2 Methods

Please see **Chapter 2** - section **2.2.3** for details on the study sample and section **2.4** for a description of the measures used in this study.

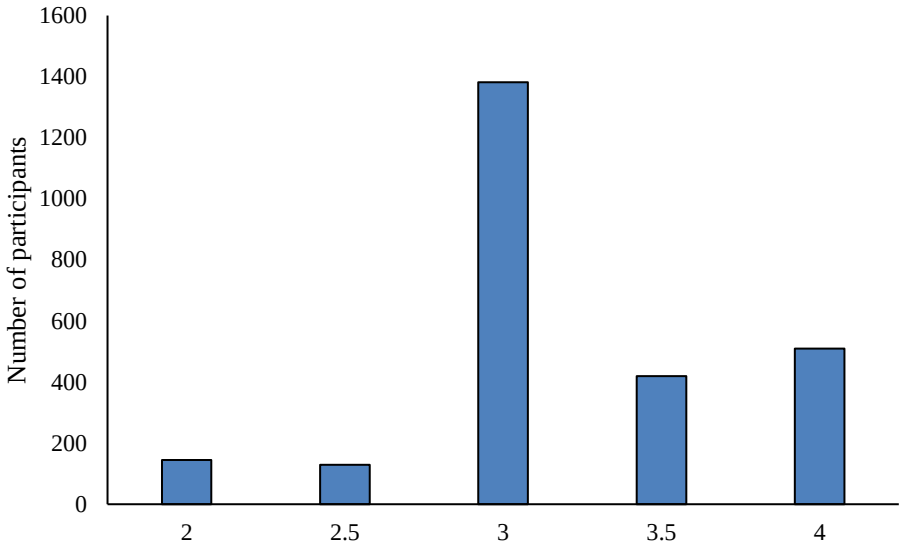
4.2.1 Additional measure – school quality

In an exploratory final modelling step, I controlled for school quality, using Ofsted ratings as my indicator. Ofsted is a governmental department responsible for periodically inspecting state schools in the UK. Schools are rated on a scale of 1 (inadequate) to 4 (outstanding), based on the outcome of an inspection, with poorly rated schools assessed more frequently. Ratings are based on 4 criteria: quality of educational provision, school environment and the impact on pupils' behaviours and attitudes, the extent to which schools provide personal development opportunities for pupils, and the effectiveness of leadership and management (GOV.UK, 2024). I used the average rating during the period of 2014-2019 to reflect school quality. If no ratings were carried out in that period, the average of the two

ratings given closest in time to this period was used. **Figure 4.1** shows the spread of school quality ratings.

Figure 4.1

Number of pupils by school quality rating.



4.2.2 Data preparation and assumption checks

Correcting for age at working memory testing.

Due to the cognitive data collection schedule being largely determined by schools' availability, other than within schools, there was no direct correspondence between participants age at T1 testing and their age at T2 testing or the age at which they sat their national exams. For instance, there was up to a 2-year difference between participants in terms of when they completed the test battery in different testing phases. This was problematic since age correlated with task performance in the previous study. Therefore, I needed to correct for this source of noise and clustering in the data.

Age at testing (recorded in Psytools) was regressed out from T1 and T2 working memory measures prior to the main analysis. The residuals from these univariate models were saved and used as the outcome measures in my structural equation models.

Confirmatory factor analysis

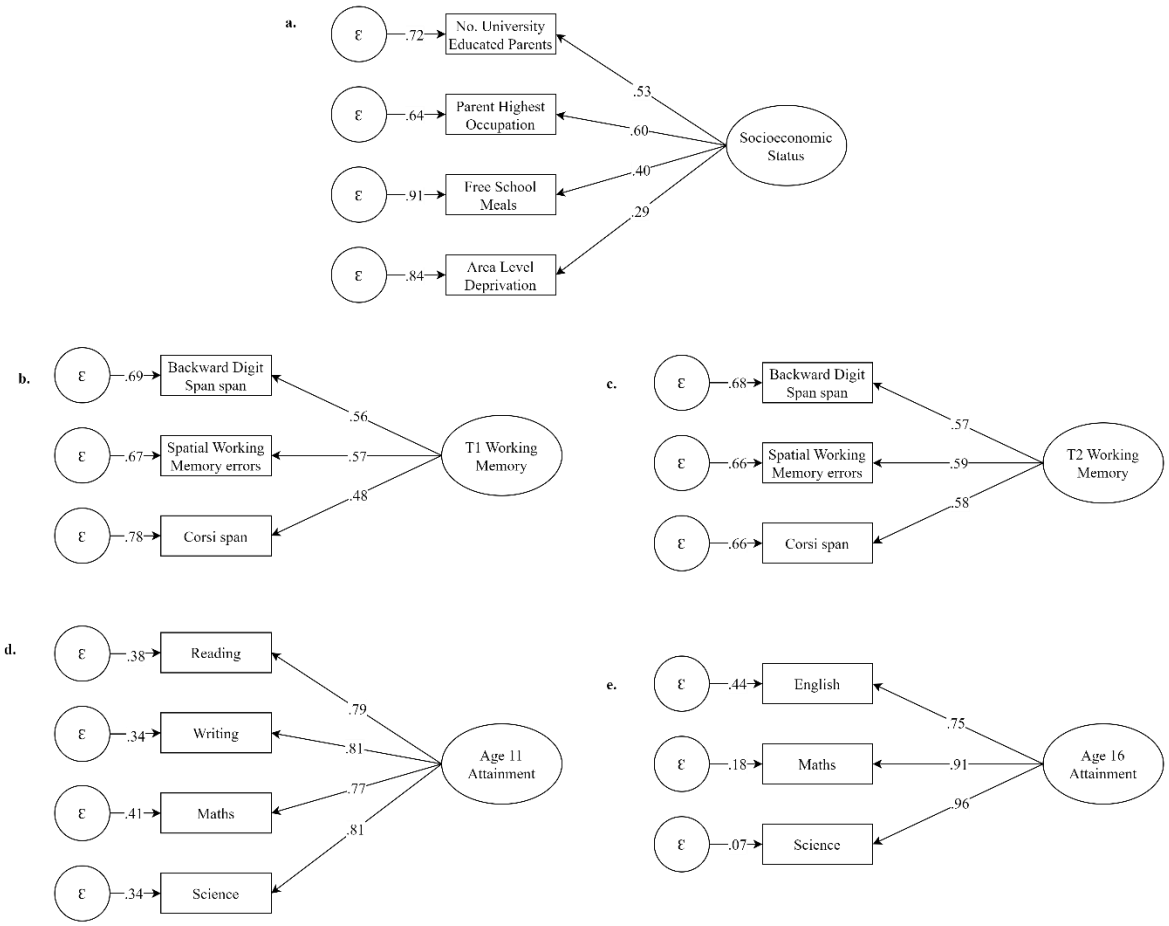
I then checked whether single factors would provide good fits for the working memory measures at T1 and T2 (with age at testing regressed out) and the attainment measures at age 11 and age 16 (again, with age at testing regressed out). I used lavaan's cfa() function with maximum likelihood estimation to carry out confirmatory factory analysis on each group of variables. SWM error scores were reversed such that a higher score now indicated better performance as with the BDS and Corsi.

I specified that oblique rotation should be used, to allow for correlations between the observed variables beyond those captured by the factors; note that these give slightly different factor loadings to the factors in the later structural equation models presented in this chapter as structural equation modelling does not rotate factor loadings. Factor loadings of the first observed variable in each model were fixed to 1 to ensure that factors made up of only three observed variables were identified.

Model fit was acceptable for age 11 attainment (CFI = .99; RMSEA = .08) but could not be computed for the other factors. Since these consisted of three observed variables each, they were just identified. All loadings were fair to excellent according to Comrey and Lee's (1992) criteria and significant at $p < .001$**. Figure 4.2** gives path diagrams of the factors. I previously showed that the socioeconomic status indices loaded onto a single factor (see Chapter 3) but a path diagram for this factor is presented alongside the others in **Figure 4.2** for ease of reading.

Figure 4.2

Path diagrams showing the loadings and error variances for **a.** the socioeconomic status factor, **b.** the T1 working memory factor, **c.** the T2 working memory factor, **d.** the age 11 attainment factor, and **e.** the age 16 attainment factor.



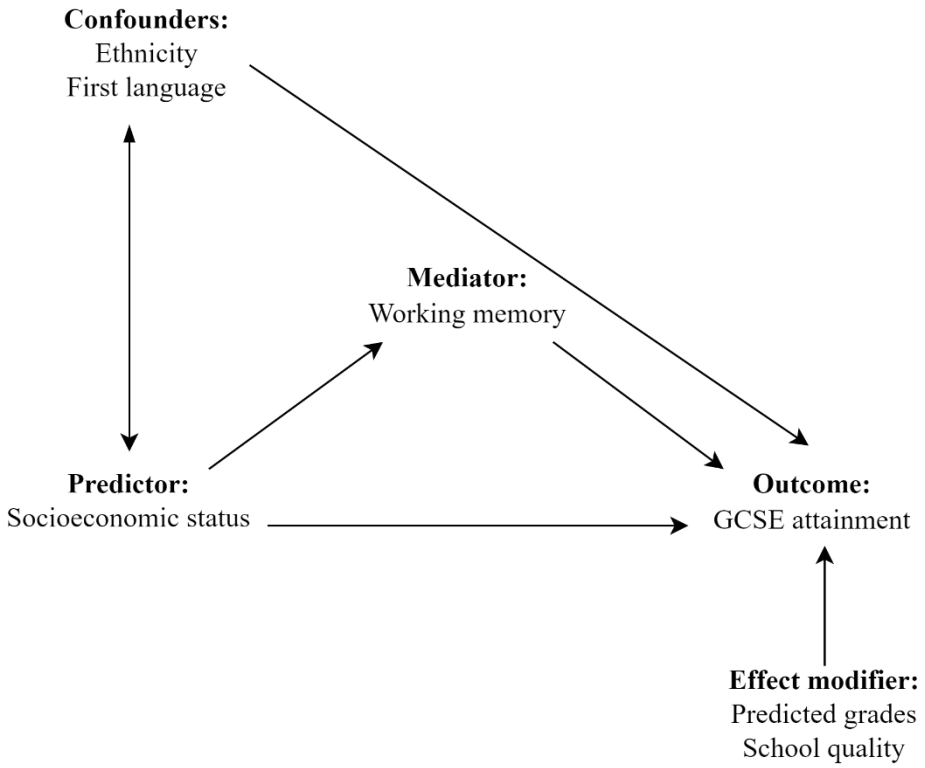
Identifying how to model demographic controls.

Next, I identified whether and how demographic measures that I had available could influence the socioeconomic status to attainment association using directed acyclic graphs

(DAGs) following (Digitale et al., 2022, see **Chapter 4 Appendices: Appendix A**). **Figure 4.3** shows my DAG.

Figure 4.3

Directed acyclic graph following Digitale et al. (2022) which lays out the likely effects of different demographic factors on the relationship between socioeconomic status and attainment.



Note. This DAG shows only the key paths tested. For path diagrams of the full models please see **Figures 4.3-5** and **4.10**.

Through creating DAGS, I concluded that ethnicity and first language status could act as confounders of the relationship between socioeconomic status and attainment. Hence, I explored the extent to which average socioeconomic status and GCSE attainment differed by ethnicity and first language status (**Table 4.1**). CIs overlapped for socioeconomic status and

GCSEs for White and mixed-race pupils, so I decided to group them and include them as the reference category. Means differed from other groups, however for Black and Asian pupils. In terms of first language, pupils who were bilingual from birth and pupils who did not have English as a first language overlapped in terms of socioeconomic status but not attainment, so I decided to keep the three groups separate.

Table 4.1

Mean [95% CIs] socioeconomic status and GCSE factor scores for the different ethnicity and first language groups in SCAMP.

		Socioeconomic status	GCSEs
Ethnicity groups	White	0.16 [0.11, 0.21]	-0.03 [-0.10, 0.03]
	Black	-0.01 [-.06, 0.05]	-0.24 [-0.33, -0.16]
	Asian	-0.22 [-0.27, -0.17]	0.22 [0.15, 0.29]
	Mixed	0.12 [0.04, 0.19]	0.00 [-0.11, 0.11]
First language groups	Monolingual English	0.12 [0.09, 0.16]	-0.04 [-0.09, 0.01]
	Bilingual from birth	-0.16 [-0.21, -0.10]	0.12 [0.05, 0.19]
	English not first language	-0.14 [-0.19, -0.09]	-0.03 [-0.12, 0.05]

A subset of the participants had predicted grades as a result of lost schooling due to the Covid pandemic, having been scheduled to sit their GCSEs in summer 2020. In the UK, teacher assessed grades awarded at 16 were around 30% lower than aged 11 predicted grades for pupils living in the most deprived areas and around 30% higher for those living in the most affluent areas (Anders et al., 2023). I was therefore concerned that this could act as an effect modifier, amplifying socioeconomic status-attainment associations in a subset of my participants. However, I found that only two pupils had predicted grades, so I did not include this as a control in any of the models.

I also identified that school quality could act as an effect modifier, since previous studies have suggested that high quality schooling can compensate for the negative effects of poverty on attainment (e.g., Alexander et al., 2007; Downey et al., 2004).

4.2.3 Analysis plan

Consistent with Donati et al. (2019), I started with simple structural equation models, treating all key variables as factors so I could assess whether more complex models were better fits for the data. I first established whether the T1 and T2 working memory measures were significantly correlated with the socioeconomic status measures (socioeconomic status factor, parent education, parent occupation, FSM status and area deprivation) and age 16 attainment measures (GCSE factor, GCSE English grade, GCSE maths grade and GCSE science grade). Next, I tested whether the socioeconomic status factor significantly predicted the GCSE factor, controlling for the age 11 attainment factor.

I then tested whether change in the working memory factor from early (T1: 10-13 years, mean age 12.06 years) to mid-adolescence (T2: 13-15 years, mean age 14.29 years) was significantly predicted by the socioeconomic status factor and significantly predictive of the GCSE factor (controlling for the age 11 attainment factor; model 1). To specify model 1, I followed the latent change score modelling procedure laid out in Kievit et al. (2018). This solves the problem of creating latent factors for different timepoints when there are high correlations between the same measures taken at different timepoints (e.g., in this study I wanted to create age 12 and age 14 working memory factors but needed to account for the correlations between age 12 and age 14 BDS span).

I then separated out attainment and working memory measures (model 2) and socioeconomic status was decomposed into its different indices last (model 3). The order in which I decided to increase model complexity was determined by several factors. First, I

wanted to provide the closest replication of Donati et al. and Albert et al.'s (2020) results and both studies treated working memory as a factor and used a composite or unitary index of socioeconomic status but explored subject specific associations. Second, previous research in adolescents suggested that working memory is more relevant for certain subjects and that there may be some differential effects of visuospatial and verbal working memory on different subjects (Albert et al., 2020; Donati et al., 2019) but I had less strong theoretical motivation to expect socioeconomic status specific associations. Finally, I wished to maximise statistical power (most data were missing on socioeconomic status, and none was missing on attainment). In each specific effects model, I estimated the covariance between different working memory measures at T1, different working memory measures at T2, attainment measures at age 11 and attainment measures at age 16. In the final model, I also estimated the covariance between socioeconomic status indices.

I ran each of the models described above twice, the second time controlling for ethnicity and first language status. These dummy coded variables were covaried with the socioeconomic status factor/indices and regressed onto the GCSE attainment factor/individual measures. Model fit for the two versions of the same model were compared and the better fitting model was interpreted.

I planned to run mediation analysis only on the best fitting model to minimise the multiple testing problem. I used Monte Carlo simulations to test the mediation paths, as running sufficient numbers of Bootstrapped samples in combination with FIML estimation is much less computationally efficient.

I controlled for Ofsted rated school quality as a follow up step because it was not central to answering the research questions. My motivation to control for school quality was partly to check that my results were not due to the cluster sampling technique, as school

quality may explain the socioeconomic status effects on attainment given that it is likely correlated with socioeconomic status.

As a final robustness check, I reran models 1-3 including the auxiliary variables school type (dummy coded: community versus academy, foundation/voluntary versus academy), duration of testing session (continuous), and percentage of pupils in the school on Free School Meals (continuous) following the saturated correlates approach (Graham, 2003). Results are reported in section **4.3.3** and **Chapter 4 Appendices E** and **F**.

I report the robust CFI and RMSEA for each model and interpret them in line with widely used criteria for model fit described in **Chapter 2** (section **2.7**). When I refer to standardised betas, these are the std.all (fully standardised) solutions from sem(). *N* for all models = 2,726.

4.3 Results

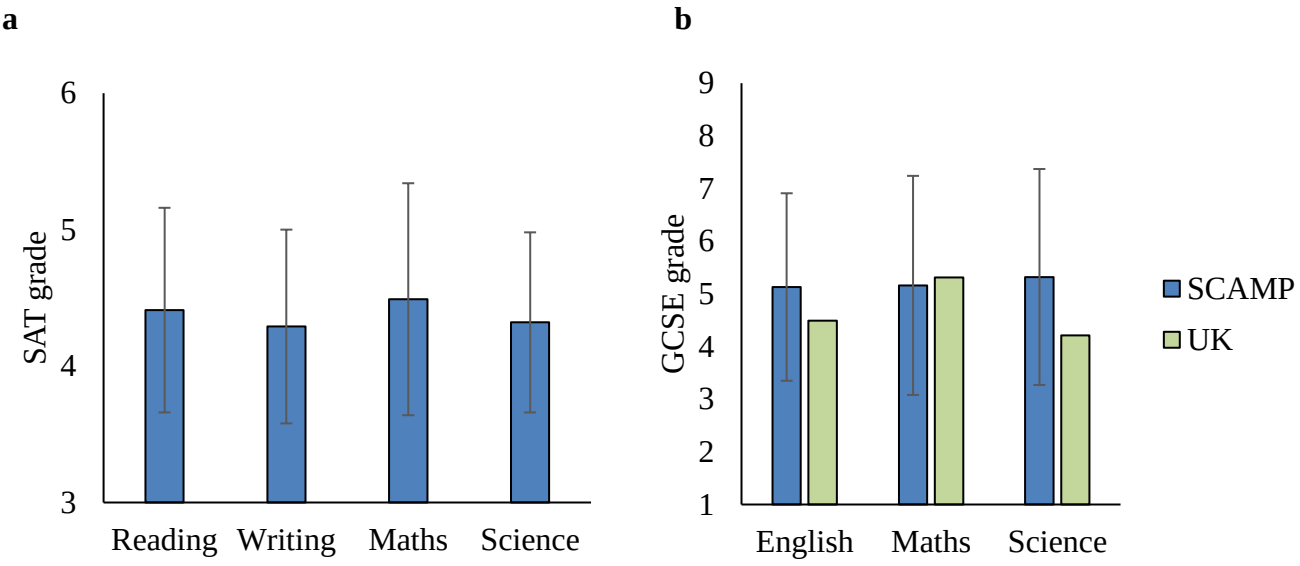
4.3.1 Descriptives

Ninety one percent of the SCAMP sample met or exceeded the expected standard (grade 4) in reading at age 11, compared to 86% of pupils in the UK as a whole in 2013 (when most SCAMP participants were in the final year of primary school; Middlemas, 2013). The subsample also exceeded national figures in their maths SATs (92% versus 85%) as well as their teacher assessed writing (91% versus 83%) and science assessments (91% versus 88%; see **Figure 4.4a** for the averages by subject for the SCAMP subsample).

Compared to the 2018 national GCSE results (when most SCAMP participants sat their GCSEs), pupils scored slightly above average in English, slightly below in maths and notably better in science (**Figure 4.4b**). The majority of pupils obtained higher than a grade 4 (standard pass). Performance higher than the national average is typical of pupils from London (see section **5.2** for further discussion of London effects).

Figure 4.4

Mean scores in **a.** different SAT/teacher assessed subjects at age 11 in the SCAMP subsample and **b.** GCSE core subjects in the SCAMP subsample compared to the national averages. Error bars reflect standard deviations.



Note. Y axes are scaled based on the range of possible scores for the assessment. National averages are from Think Student (2021).

4.3.2 Correlations and assumption checks

First, I established that the observed and latent variables I hypothesised to be related were significantly correlated. **Table 4.2** shows the pairwise complete parametric correlations for all key variables of interest.

Table 4.2

Correlation matrix for the predictor, mediating and control variables.

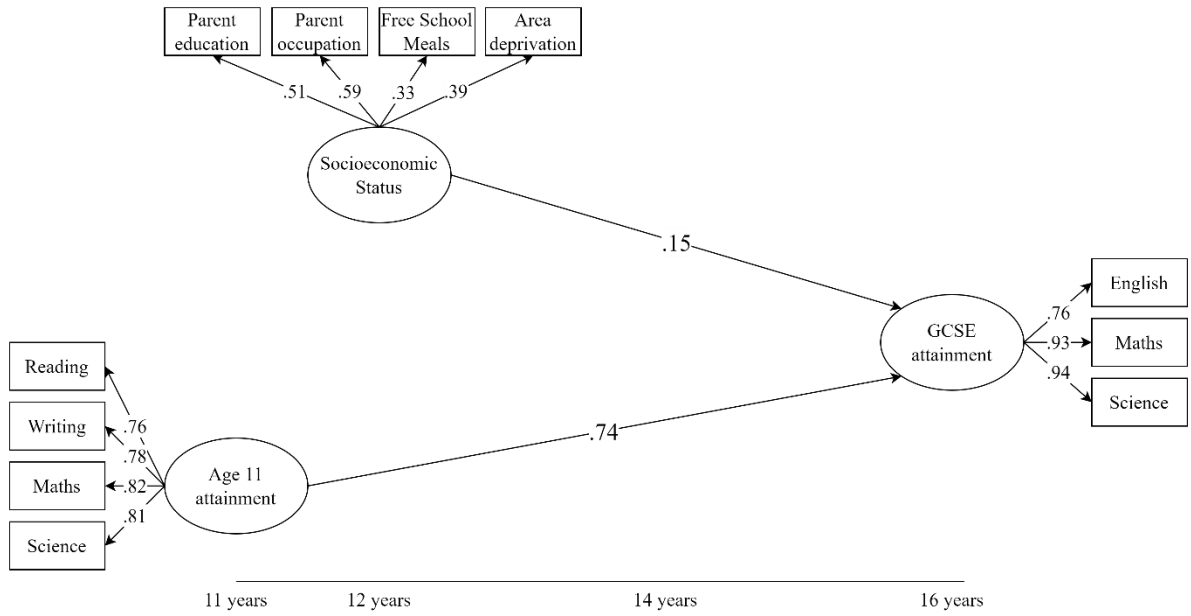
	M (SD)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. Parent education	0.99 (0.89)	*SES - SES associations*																				
2. Parent occupation	5.07 (1.94)	**.38**																				
3. Income (FSM)	0.19 (0.39)	**-.17**	**-.13**																			
4. Area deprivation	3.81 (1.25)	**-.19**	**-.23**	**.18**																		
5. Socioeconomic status.f	0.00 (0.71)	**.79**	**.83**	**-.42**	**-.55**																	
6. T1 BDS	0.00 (0.86)	**.07**	**.06**	**-.05**	-.02	**.08**	*Working memory – working memory associations*															
7. T1 SWM	0.00 (13.14)	-.05	**-.05**	**.05**	**.07**	**-.08**	**-.26**															
8. T1 Corsi span	0.00 (0.75)	.01	.05	**-.06**	-.01	**.04**	**.32**	**-.27**														
9. T1 WM.f	0.00 (0.70)	**.06**	**.07**	**-.07**	**-.05**	**.09**	**.79**	**-.68**	**.78**													
10. T2 BDS	0.00 (0.96)	**.07**	**.08**	**-.09**	-.04	**.10**	**.50**	**-.27**	**.33**	**.50**												
11. T2 SWM	0.00 (12.65)	-.01	**-.05**	**.06**	**.06**	**-.06**	**-.25**	**.34**	**-.28**	**-.38**	**-.32**											
12. T2 Corsi	0.00 (0.89)	.04	**.11**	-.05	**-.06**	**.10**	**.27**	**-.27**	**.48**	**.46**	**.33**	**-.34**										
13. T2 WM.f	0.00 (0.72)	**.05**	**.10**	**-.09**	**-.06**	**.11**	**.46**	**-.38**	**.43**	**.55**	**.79**	**-.80**	**.76**									
14. Reading 11y	0.00 (0.75)	**.11**	**.16**	**-.11**	**-.08**	**.17**	**.31**	**-.22**	**.22**	**.33**	**.31**	**-.26**	**.24**	**.34**	*Attainment – attainment associations*							
15. Writing 11y	0.00 (0.71)	**.15**	**.18**	**-.10**	**-.08**	**.18**	**.33**	**-.22**	**.25**	**.35**	**.35**	**-.27**	**.25**	**.37**	**.65**							
16. Maths 11y	0.00 (0.85)	**.15**	**.15**	**-.10**	**-.09**	**.18**	**.37**	**-.31**	**.34**	**.44**	**.42**	**-.32**	**.39**	**.46**	**.61**	**.60**						
17. Science 11y	0.00 (0.66)	**.15**	**.18**	**-.12**	**-.10**	**.19**	**.31**	**-.25**	**.27**	**.36**	**.33**	**-.26**	**.28**	**.37**	**.61**	**.66**	**.64**					
18. Age 11 attainment.f	0.00 (0.93)	**.17**	**.20**	**-.12**	**-.10**	**.21**	**.39**	**-.29**	**.32**	**.43**	**.41**	**-.32**	**.34**	**.45**	**.84**	**.87**	**.82**	**.87**				
19. English GCSE	0.00 (1.78)	**.20**	**.21**	**-.16**	**-.12**	**.25**	**.34**	**-.25**	**.31**	**.39**	**.39**	**-.29**	**.29**	**.41**	**.52**	**.57**	**.54**	**.54**	**.64**			
20. Maths GCSE	0.00 (2.08)	**.20**	**.19**	**-.18**	**-.12**	**.24**	**.38**	**-.32**	**.39**	**.47**	**.46**	**-.35**	**.41**	**.50**	**.48**	**.50**	**.73**	**.58**	**.67**	**.68**		
21. Science GCSE	0.00 (2.05)	**.22**	**.20**	**-.18**	**-.12**	**.25**	**.37**	**-.30**	**.35**	**.44**	**.43**	**-.32**	**.37**	**.47**	**.50**	**.51**	**.65**	**.56**	**.65**	**.72**	**.87**	
22. GCSE.f	0.00 (0.97)	**.22**	**.21**	**-.19**	**-.13**	**.26**	**.39**	**-.32**	**.37**	**.47**	**.46**	**-.35**	**.39**	**.50**	**.52**	**.54**	**.69**	**.59**	**.68**	**.77**	**.93**	**.99**

Note. Emboldened correlations are significant at $p < .05$. f signifies factors. Higher scores on the BDS, Corsi span, and WM factor reflect better working memory, higher scores on the SWM reflect lower working memory. Values for working memory are after regressing out age.

Next, I tested whether socioeconomic status significantly predicted GCSE attainment, controlling for age 11 attainment (all entered as factors; **Figure 4.5**). Model fit was within acceptable limits according to CFI (.94) and RMSEA (.09). All observed variables significantly loaded onto their specified latent variable. Socioeconomic status and age 11 attainment explained 64% of the variance in GCSE attainment. Supporting H1, both factors were significant predictors (all $p < .001$), however the effect of prior attainment on GCSE attainment (standardised effect size [95% CI] β =.74 [.71, .76], raw β = 1.22 [1.13, 1.31]) was nearly four times larger than the effect of socioeconomic status (standardised β = .15 [.10, .19], raw β = 0.25 [0.17, 0.32]).

Figure 4.5

Path diagram showing the association between age 11 school attainment (SATs), socioeconomic status at age 12 and age 16 attainment (GCSEs).



Note. All paths are significant at $p < .001$, values on the paths are standardised βs.

Rerunning the model controlling for ethnicity and first language status did not improve model fit (CFI = .87, RMSEA = .10) or substantially attenuate or qualitatively change the associations between socioeconomic status, age 11 attainment and age 16 attainment. The addition of these controls did, however, increase the strength of the socioeconomic status to age 16 attainment association by .10. Please see **Chapter 4 Appendices: Appendix B** for further details of the model rerun with ethnicity and first language controls.

Reruning the model with the addition of auxiliary variables slightly worsened model fit according to CFI (.92) but slightly improved model fit according to RMSEA (.08). Both were still within acceptable ranges. The strength of the socioeconomic status to GCSE path reduced to $\beta = .11$ [.06, .15] but remained significant at $p < .001$.

4.3.3 Model 1. Latent change model testing whether socioeconomic status and working memory predict GCSE attainment controlling for age 11 attainment.

To test H2, that change in working memory over early to mid-adolescence would significantly predict age 16 attainment controlling for age 11 attainment and socioeconomic status, I added T1, T2 and delta working memory factors to the model. Variance explained increased to 75% and model fit improved according to RMSEA (.06) and CFI (.94) remained the same.

Change in working memory from 12 to 14 years explained a significant amount of variance in age 16 attainment, consistent with H2. This association was small but more than twice that of the socioeconomic status – attainment association. The socioeconomic status – attainment association reduced by a third with the addition of the working memory factor, relative to the previous model, and this path was no longer statistically significant. The socioeconomic status factor association with change in working memory over adolescence

was also not significant (**Table 4.3, Figure 4.6**). Model fit did not change substantively with the addition of auxiliary variables (CFI = .93; RMSEA = .06), nor did parameter estimates (please see **Chapter 4 Appendices: Appendix C**).

Table 4.3

Parameter estimates, CIs and *p*-values for the key paths shown in **Figure 4.6**.

	Std. β [95% CI]	**Raw β [95% CI]**	***p*-value**
Socioeconomic status -> GCSEs	.10 [-.07, .26]	0.19 (-0.14, 0.52)	.250
Age 11 attainment -> GCSEs	.49 [.41 .56]	0.97 [0.75, 1.20]	< .001
Δ working memory -> GCSEs	.43 [.33, .52]	3.71 [1.97, 5.44]	< .001
Socioeconomic status -> Δ working memory	.16 [-.23, .54]	0.04 [-0.05, 0.12]	.414

Figure 4.6

Path diagram showing the latent change score model ran to establish whether change in working memory over early to mid-adolescence predicts attainment at 16 (GCSEs), controlling for socioeconomic status and prior attainment (SATs).

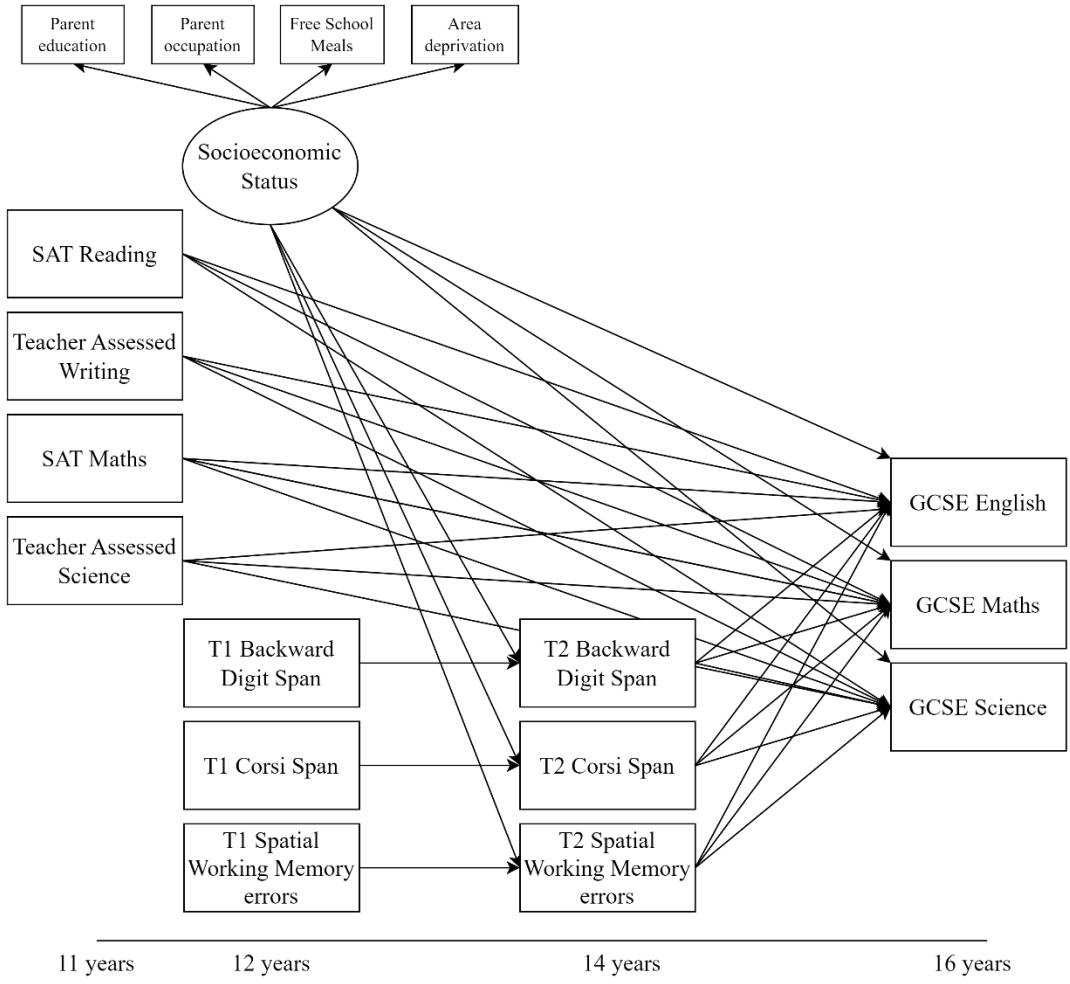
Note. All paths are significant at $p < .05$, values on the paths are standardised βs.

4.3.4 Model 2. Testing for specificity of working memory to attainment relationships.

I reran model 1, now treating working memory measures and attainment measures as individual predictors (**Figure 4.7**). This model tested the hypothesis that the effects of working memory on attainment would be stronger for maths and science than English (H3). It was also designed to test the prediction that verbal working memory would have stronger associations with attainment than visuospatial working memory (H4i) and that visuospatial working memory would be more strongly related to maths performance than to performance in other subjects (H4ii). Model fit was marginal (CFI = .91, RMSEA = .09).

Figure 4.7

Path diagram of all the regression paths tested in structural equation model 2.



Note. Covariances between measures taken at the same time point are not shown here but detailed in the main text. For a simplified path diagram of this model detailing the β coefficients for the key paths tested, see **Figure 4.8**.

The model explained most variance in maths attainment at 16 (R^2 = .54), then science (R^2 = .46), and least in English attainment (R^2 = .40). Model fit substantially worsened controlling for ethnicity and first language status (CFI = .34, RMSEA = .28), so I interpret the model without the added demographic controls below. The parameter estimates for the model with demographic controls are not detailed in the Appendix as solutions are likely to be unreliable. RMSEA (.07) improved with the addition of auxiliary variables, but CFI was unchanged. Most parameter estimates did not substantially change, although socioeconomic status to attainment associations reduced by around one third (see **Chapter 4 Appendices: Appendix D**).

Covariances between all T1 working memory measures, all T2 working memory measures, all age 11 attainment measures and GCSE measures were significant at $p < .001$ (**Figure 4.8** and **Chapter 4 Appendices: Appendix E**). Performance on a working memory task at age 12 significantly predicted performance on that task at 14. Span tasks showed greater longitudinal stability (**Table 4.4**).

Table 4.4

Standardised and unstandardised coefficients and CIs for the associations of the socioeconomic status factor and T1 working memory measures with T2 working memory skills.

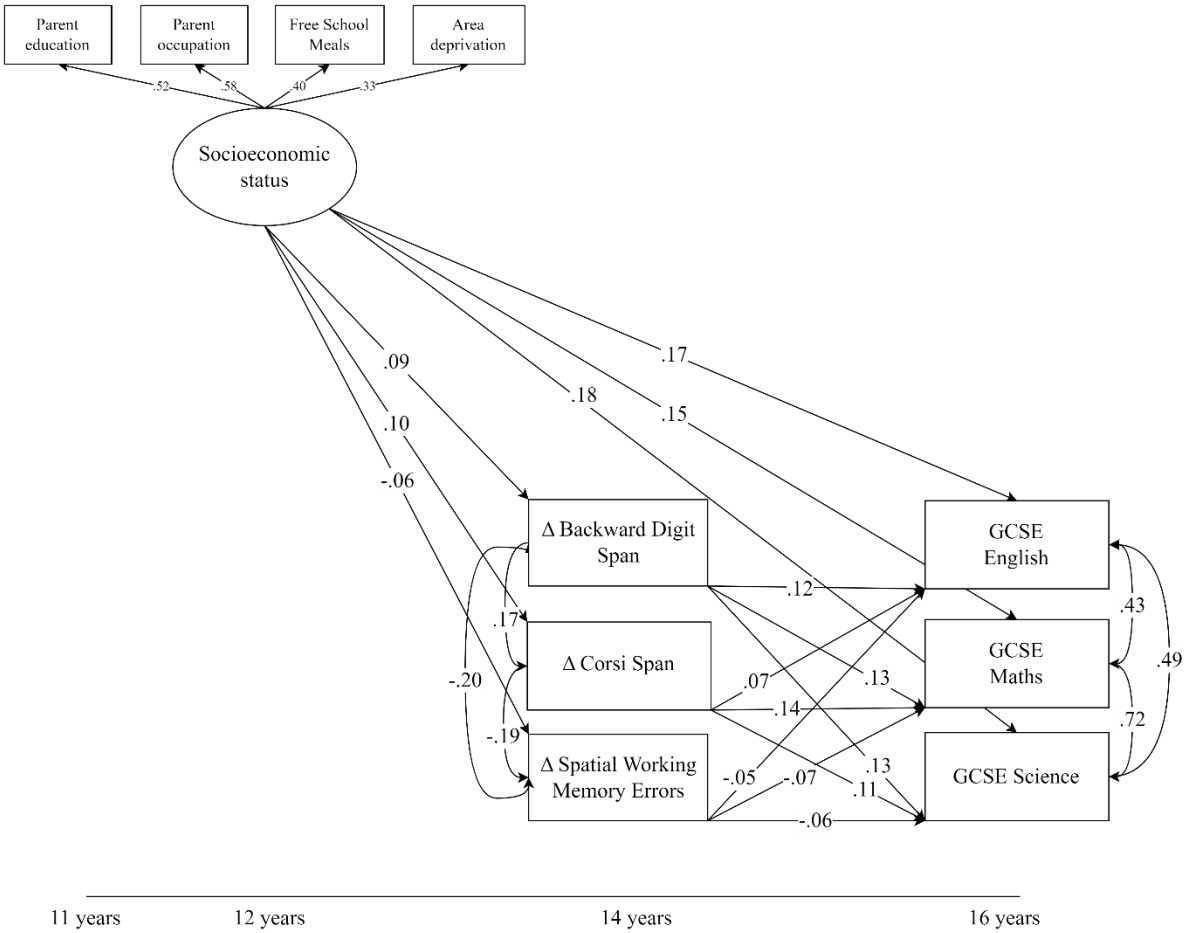
	Std. β (95% CIs)	**Raw β (95% CIs)**
Socioeconomic status factor -> T2 BDS span	.09 (.04, .14)***	0.09 (0.04, 0.13)
Socioeconomic status factor -> T2 Corsi span	.11 (.02, .18)*	0.09 (0.02, 0.16)

Socioeconomic status factor -> T2 SWM errors	-.06 (-.12, -.01)*	-0.80 (-1.45, -0.08)
T1 BDS span -> T2 BDS span	.48 (.45, .51)***	0.53 (0.49, 0.56)
T1 Corsi span -> T2 Corsi span	.47 (.41, .52)***	0.55 (0.48, 0.62)
T1 SWM errors -> T2 SWM errors	.31 (.27, .35)***	0.30 (0.26, 0.33)

Note. * $p < .05$, ** $p < .01$, *** $p < .001$. BDS = Backward Digit Span; SWM = Spatial Working Memory task.

Figure 4.8

Simplified path diagram of model 2 showing the associations between socioeconomic status, working memory measures at 14 (controlling for performance on those tasks at 12) and age 16 attainment.



Note. For the full path diagram of the model, please see **Figure 4.7** All paths are significant at $p < .05$. Values on the paths are standardised estimates.

All age 11 attainment variables had small and significant associations with GCSE English. Similarly, all age 11 attainment to GCSE science associations were significant and of small (reading, writing and science) to moderate magnitude (maths). Age 11 reading and writing did not significantly predict GCSE maths. However, maths and science attainment at 11 showed strong and small significant associations with GCSE maths, respectively (**Table 5**).

Socioeconomic status had small but significant longitudinal associations with all age 14 working memory measures (**Table 4.5, Figure 4.8**) and attainment in all subjects at age 16 (**Table 4.4, Figure 4.8**). Socioeconomic status positively predicted BDS, Corsi span and age 16 attainment measures and negatively predicted SWM. In terms of attainment, socioeconomic status effects were slightly larger on English and science than maths.

Table 4.5

Standardised and unstandardised coefficients and CIs for the associations of age 11 attainment measures, the socioeconomic status factor, and T2 working memory measures with attainment at age 16 in English, maths and science.

	GCSE English		**GCSE Maths**		**GCSE Science**	
	Std. β [95% CIs]	**Raw β [95% CIs]**	**Std. β [95% CIs]**	**Raw β [95% CIs]**	**Std. β [95% CIs]**	**Raw β [95% CIs]**
Reading 11y	.14 [.09, .18]***	0.30 [0.20, .40]	-.02 [-.06, .02]	-0.06 [-0.16, .04]	.06 [.02, .10]**	0.15 [0.04, .26]
Writing 11y	.25 [.21, .30]***	0.59 [0.48, .70]	.01 [-.03, .06]	0.04 [-0.07, .15]	.05 [.00, .09]*	0.12 [0.00, .24]
Maths 11y	.15 [.10, .19]***	0.29 [0.20, .38]	.56 [.53, .60]***	1.27 [1.18, 1.36]	.40 [.36, .45]***	0.91 [0.81, 1.00]
Science 11y	.14 [.09, .18]***	0.35 [0.23, .46]	.16 [.12, .20]***	0.47 [0.35, .59]	.18 [.13, .22]***	0.51 [0.38, .64]
Socioeconomic status.f	.17 [.13, .22]***	0.29 [0.21, 0.37]	.15 [.11, .19]***	0.28 [0.20, 0.36]	.18 [.13, .22]***	0.34 [0.25, 0.42]
T2 BDS span	.12 [.09, .16]***	0.22 [0.15, 0.28]	.13 [.09, .16]***	0.25 [0.19, 0.32]	.13 [.10, .17]***	0.27 [0.20, 0.34]
T2 Corsi span	.07 [.02, .12]**	0.13 [0.03, 0.23]	.14 [.10, .19]***	0.31 [0.21, 0.40]	.11 [.06, .16]***	0.23 [0.13, 0.33]
T2 SWM errors	-.05 [-.09, -.01]*	-0.01 [-0.01, 0.00]	-.07 [-.10, -.03]***	-0.01 [-0.02, -0.01]	-.06 [-.10, -.03]***	-0.01 [-0.02, 0.00]

Note. * $p < .05$, ** $p < .01$, *** $p < .001$. .f signifies factors. BDS = Backward Digit Span; SWM = Spatial Working Memory task.

Change in all working memory measures had small and significant associations with attainment. BDS and Corsi span were equally as good predictors of GCSE maths attainment. However, the strength of the association of BDS with GCSE English was nearly twice as large as the associations between visuospatial working memory measures and GCSE English. For science, BDS was also the strongest working memory predictor, but this was closely followed by Corsi span. SWM errors had the smallest associations with attainment across subjects (**Table 4.5**).

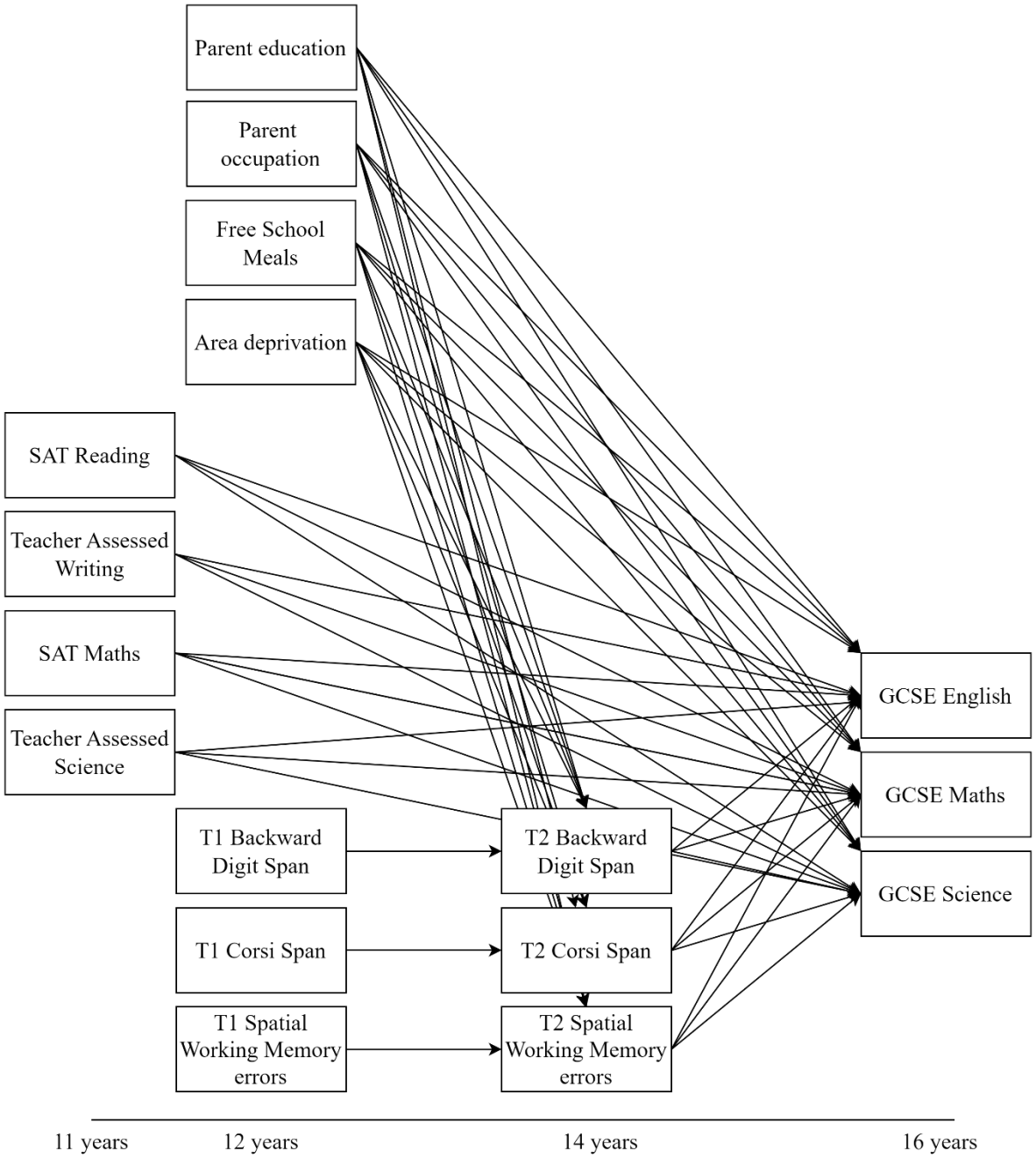
Contrary to my expectation that working memory associations with attainment would be stronger for maths and science (H3), beta coefficients for associations with BDS were virtually identical across subjects (**Table 4.5**). Results for the visuospatial tasks were consistent with H3, but overlapping CIs suggested that the differences between subjects were not statistically significant, so the prediction was not supported. Results were, however, consistent with my prediction that verbal working memory would be a better predictor of attainment than visuospatial working memory (H4i) when comparing BDS span to SWM errors but not when comparing Corsi span to SWM errors. However, the CIs for the BDS – SWM error comparison overlapped in all cases, so H4i was not supported. Further, whilst visuospatial working memory was more strongly related to maths than to other subjects, CIs overlapped in all cases so H4ii was not supported.

4.3.5 Model 3. Testing for specificity of socioeconomic status associations with attainment and working memory

As a final step in increasing model complexity, I removed the socioeconomic status factor and instead treated the four socioeconomic status indices as individual predictors. This was done to test the prediction that all socioeconomic status indices would predict age 16 attainment but that only parent occupation and Free School Meals status would predict changes in working memory (H5) (**Figure 4.9**). Model fit was marginally acceptable (CFI = .91; RMSEA = .10, Browne & Cudeck, 1992) and the model explained 54% of the variance in maths, 45% of the variance in science and 38% of the variance in English attainment at 16 over and above performance in different subjects at age 11. Rerunning the model controlling for ethnicity and first language status worsened model fit according to the CFI (.87) and RMSEA was unchanged, so I interpret the model without these controls below (see **Chapter 4 Appendices: Appendix F** for details of this model). Model fit according to RMSEA (.08) was improved with the addition of auxiliary variables, but parameter estimates were largely unchanged (see **Chapter 4 Appendices: Appendix G**).

Figure 4.9

Path diagram of all the regression paths tested in structural equation model 3.

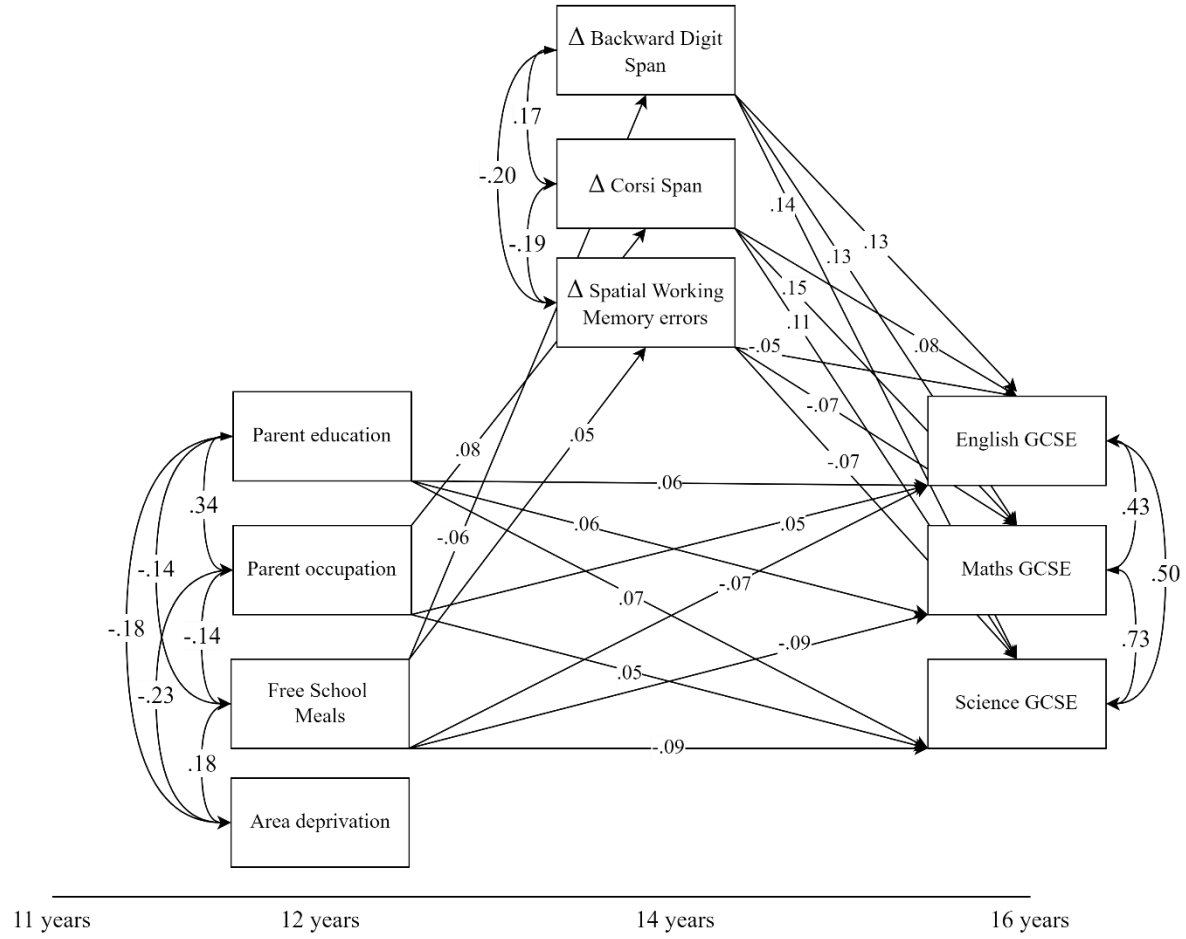


Note. Covariances between measures taken at the same time point are not shown here but detailed in the text above and below. For a simplified path diagram of this model which details the β coefficients for the key paths, please see **Figure 10**.

Covariances between all socioeconomic status indices were significant at $p < .001$, as were covariances between all age 11 attainment measures, T1 working memory measures, T2 working memory measures, and age 16 attainment measures (**Figure 4.10** and **Appendix D**). **Table 4.6** gives the parameter estimates for the associations of age 11 attainment measures, socioeconomic status indices, and T2 working memory measures with attainment in different subjects at age 16. **Table 4.7** gives the parameter estimates for the associations of different socioeconomic status indicators with performance on each of the working memory tasks at T2, as well as the parameter estimates for the T1~T2 associations for each working memory measure.

Figure 4.10

Simplified path diagram of model 3 showing significant associations between socioeconomic status indices, working memory measures at 14 (controlling for performance on those tasks at 12) and age 16 attainment (GCSEs).



Note. Covariances between measures taken at the same time point are not shown here but detailed in the text above and below. For the full path diagram of this model, please see **Figure 4.9**, and for the estimates of the non-significant paths, see **Tables 6 and 7**.

Table 4.6

Standardised and unstandardised coefficients and CIs for the associations of age 11 attainment measures, socioeconomic status indices, and T2 working memory measures with attainment at age 16 in English, maths and science.

	GCSE English		GCSE Maths		GCSE Science	
	Std. β [95% CIs]	**Raw β [95% CIs]**	**Std. β [95% CIs]**	**Raw β [95% CIs]**	**Std. β [95% CIs]**	**Raw β [95% CIs]**
Reading 11y	.14 [.09, .18]***	0.30 [0.20, 0.40]	-.03 [-.07, .01]	-0.06 [-0.16, 0.04]	.06 [.01, .10]**	0.14 [0.04, 0.25]
Writing 11y	.25 [.21, .30]***	0.59 [0.49, 0.70]	.02 [-.03, .06]	0.04 [-0.07, 0.15]	.05 [.00, .09]*	0.12 [0.00, 0.24]
Maths 11y	.15 [.10, .19]***	0.29 [0.20, 0.38]	.57 [.53, .60]***	1.27 [1.18, 1.36]	.40 [.36, .45]***	0.91 [0.81, 1.00]
Science 11y	.14 [.09, .18]***	0.34 [0.23, 0.46]	.16 [.12, .20]***	0.47 [0.35, 0.59]	.18 [.13, .22]***	0.51 [0.38, 0.64]
Parent education	.06 [.02, .10]**	0.12 [0.04, 0.19]	.06 [.02, .09]**	0.13 [0.05, 0.20]	.07 [.03, .10]**	0.14 [0.06, 0.22]
Parent occupation	.05 [.02, .09]**	0.05 [0.01, 0.08]	.03 [-.01, .06]	0.02 [-0.01, 0.06]	.05 [.02, .09]**	0.05 [0.02, 0.09]
Free School Meals	-.07 [-.10, -.04]***	-0.30 [-0.43, -0.16]	-.09 [-.12, -.06]***	-0.43 [-0.57, -0.29]	-.09 [-.12, .-.05]***	-0.41 [-0.56, -0.26]
Area deprivation	-.02 [-.06, .01]	-0.03 [-0.08, 0.01]	-.02 [-.05, .01]	-0.03 [-0.7, 0.02]	-.01 [-.04, .02]	-0.02 [-0.07, 0.03]
T2 BDS span	.13 [.09, .16]***	0.22 [0.16, 0.29]	.13 [.10, .16]***	0.26 [0.19, 0.32]	.14 [.10, .17]***	0.27 [0.20, 0.34]
T2 Corsi span	.08 [.03, .13]**	0.14 [0.05, 0.24]	.15 [.10, .16]***	0.32 [0.23, 0.42]	.11 [.07, .16]***	0.25 [0.15, 0.35]
T2 SWM errors	-.05 [-.09, -.01]**	-0.01 [-0.01, 0.00]	-.07 [-.10, -.04]***	-0.01 [-0.02, -0.01]	-.07 [-.10, -.03]***	-0.01 [-0.02, -0.01]

Note. * $p < .05$, ** $p < .01$, *** $p < .001$. .f signifies factors. BDS = Backward Digit Span; SWM = Spatial Working Memory task

Table 4.7

Standardised and unstandardised coefficients and CIs for the associations of socioeconomic status indices and T1 working memory measures with T2 working memory skills.

	Std. β [95% CIs]	Raw β [95% CIs]
Parent education -> T2 BDS span	.02 [-.02, .06]	0.02 [-0.02, 0.07]
Parent education -> T2 Corsi span	.00 [-.07, .07]	0.00 [-0.07, 0.07]
Parent education -> T2 SWM errors	.03 [-.02, .08]	0.40 [-0.3, 1.08]
Parent occupation -> T2 BDS span	.04 [.00, .08]	0.02 [0.00, 0.04]
Parent occupation -> T2 Corsi span	.08 [.01, .14]*	0.04 [0.01, 0.06]
Parent occupation -> T2 SWM errors	-.04 [-.08, .01]	-0.23 [-0.52, 0.05]
Free School Meals -> T2 BDS span	-.06 [-.09, -.02]**	-0.14 [-0.22, -0.05]
Free School Meals -> T2 Corsi span	-.02 [-.08, .03]	-0.05 [-0.17, 0.07]
Free School Meals -> T2 SWM errors	.05 [.01, .09]*	1.47 [0.21, 2.73]
Area deprivation -> T2 BDS span	-.01 [-.04, .03]	0.00 [-0.03, 0.02]
Area deprivation -> T2 Corsi span	-.02 [-.09, .04]	-0.02 [-0.06, 0.03]
Area deprivation -> T2 SWM errors	.03 [-.01, .07]	0.30 [-0.11, 0.70]
T1 BDS span -> T2 BDS span	.48 [.45, .51]***	0.53 [0.49, 0.56]
T1 Corsi span -> T2 Corsi span	.47 [.41, .52]***	0.54 [0.47, 0.61]
T1 SWM errors -> T2 SWM errors	.31 [.27, .34]***	0.29 [0.26, 0.33]

Note. * $p < .05$, ** $p < .01$, *** $p < .001$. .f signifies factors. BDS = Backward Digit Span; SWM = Spatial Working Memory task.

As predicted based on previous analyses (see **Chapter 3**), area deprivation and parent education level were not significantly related to change in any working memory measure; only parent occupation and Free School Meals status predicted change in working memory skills over adolescence (**Table 4.7**). More specifically, BDS span and SWM errors were significantly predicted by FSM status and Corsi span was predicted by parent highest occupation.

Contrary to predictions, area deprivation did not predict attainment in any subject at 16 (**Table 4.6**). All other socioeconomic status indices significantly predicted attainment in

each subject, except for parental occupation, which did not significantly predict age 16 maths attainment (**Table 4.6**). These results are therefore partially consistent with H5. In addition, all working memory change to attainment paths were small and significant (**Table 4.6**). Significant paths are shown in the path diagram in **Figure 4.10**.

4.3.6 Mediation analysis

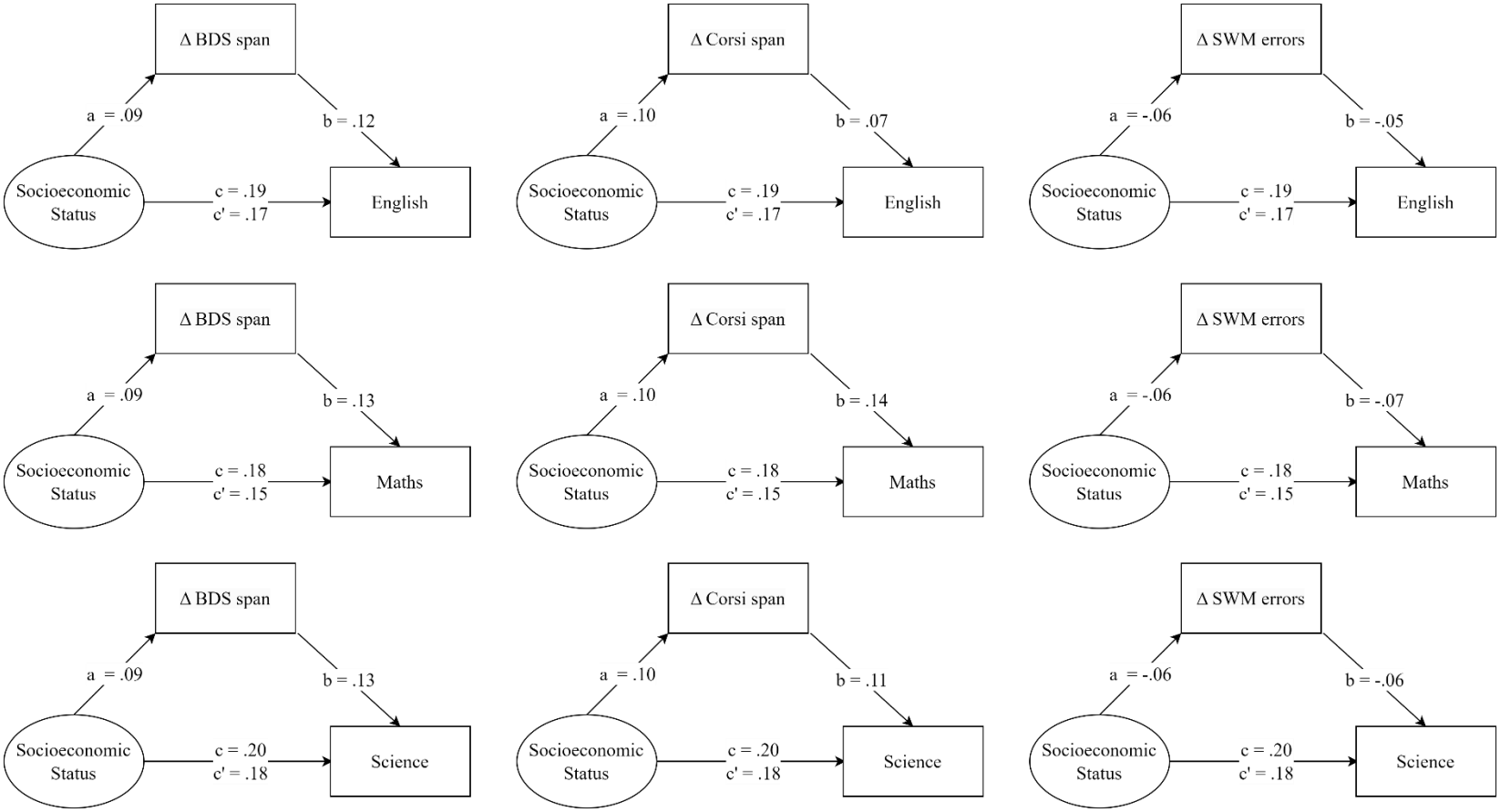
I ran mediation analyses within structural equation model 2 (the best fitting model with significant paths from socioeconomic status to working memory and socioeconomic status to attainment) to test my prediction that widening social inequalities in working memory over adolescence would explain widening social inequalities in attainment (H6) (**Figure 4.11**). 50,000 Montecarlo simulations were run using semTools to estimate 95% CIs for the indirect and total effects. Model fit was marginal (CFI = .91, RMSEA = .09).

Change in scores on the three working measures over adolescence mediated 11% of the socioeconomic status effect on age 16 English attainment, 17% for maths and 13% for science. See **Figure 4.12** for a graph of the mediation ratios by working memory measure. Montecarlo CIs for the indirect paths did not cross zero, except for the indirect effects of socioeconomic status on English attainment via Corsi span and SWM errors. No Montecarlo CIs for the direct paths, controlling for change in working memory, crossed zero (**Table 4.8**). c' < c for all school subjects, indicating partial mediation.

These results are partially consistent with H6; change in all working memory measures over adolescence mediated the relationship between socioeconomic status and maths and science attainment (controlling for age 11 attainment). However, only change in verbal working memory span mediated the relationship between socioeconomic status and English attainment.

Figure 4.11

Standardised parameter estimates for the mediation tested within model 1.



Note. c is the direct effect of socioeconomic status on GCSEs not accounting for change in working memory. Please refer to **Figure 6** for a path diagram of the full model.

Figure 4.12

Percentage of the total effect of socioeconomic status on attainment in GCSE English, Maths and Science explained by changes in different working memory measures from 12-14 years.

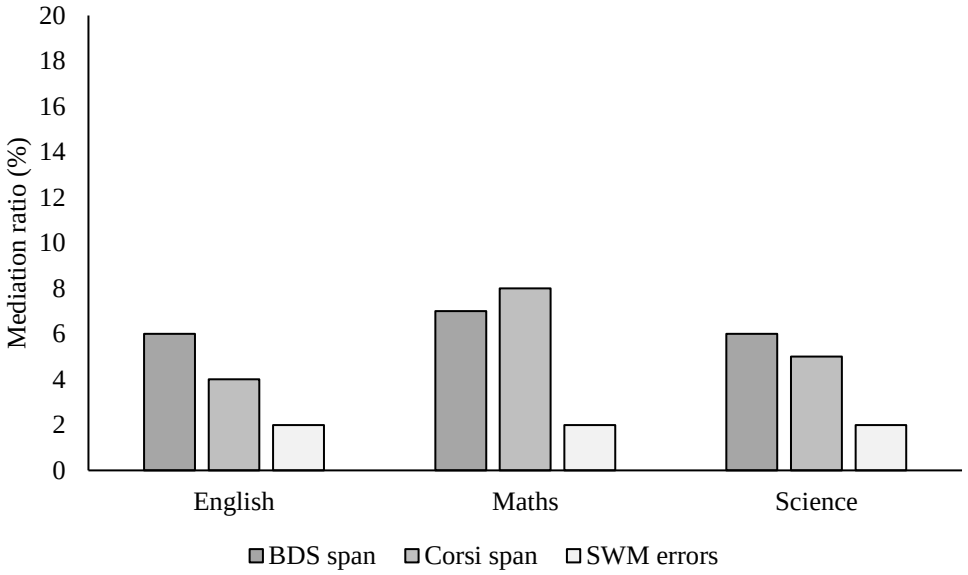


Table 4.8

Standardised beta estimates and Montecarlo 95% CIs for the indirect and indirect effects of socioeconomic status on English, maths and science attainment.

	English	**Maths**	**Science**
Indirect effects	**ab [95% CIs]**	**ab [95% CIs]**	**ab [95% CIs]**
BDS span	.01 [.01, .02]**	.01 [.01, .02]***	.01 [.01, .02]***
Corsi span	.01 [.00, .02]	.01 [.00, .03]*	.01 [.00, .02]*
SWM errors	.00 [.00, .01]	.00 [.00, .01]*	.00 [.00, .01]*
Total effect	**c [95% CIs]**	**c [95% CIs]**	**c [95% CIs]**
	.19 [.15, .24]***	.18 [.14, .22]***	.20 [.16, .25]***

Note. * $p < .05$, ** $p < .01$, *** $p < .001$. .f signifies factors. BDS = Backward Digit Span; SWM = Spatial Working Memory task

4.3.7 Controlling for school quality

In an attempt to eliminate the effect of school quality from the socioeconomic status effects on attainment, I added Ofsted school rating as a control in model 1. Ofsted rating was regressed onto the GCSE attainment factor and covaried with the socioeconomic status factor. RMSEA (.06) and CFI (.94) values indicated acceptable fit, and the model explained 75% of the variance in the GCSE factor.

Ofsted grade had a small and significant negative correlation with the socioeconomic status factor and a small and significant positive association with the GCSE attainment factor (**Figure 4.13**). Its association with attainment was around half that of the socioeconomic status to attainment relationship. Socioeconomic status became a significant predictor of GCSEs when this predictor was added, and its beta value increased by .05, showing that socioeconomic status-attainment associations were not driven by the correlation between family/neighbourhood socioeconomic status and school quality but that schools were diluting some of the effects of socioeconomic status on attainment. The socioeconomic status-working memory change association halved with the addition of Ofsted ratings. Please see **Figure 4.13** for a path diagram of model 1 after including Ofsted rating of school quality.

Supplementary analysis

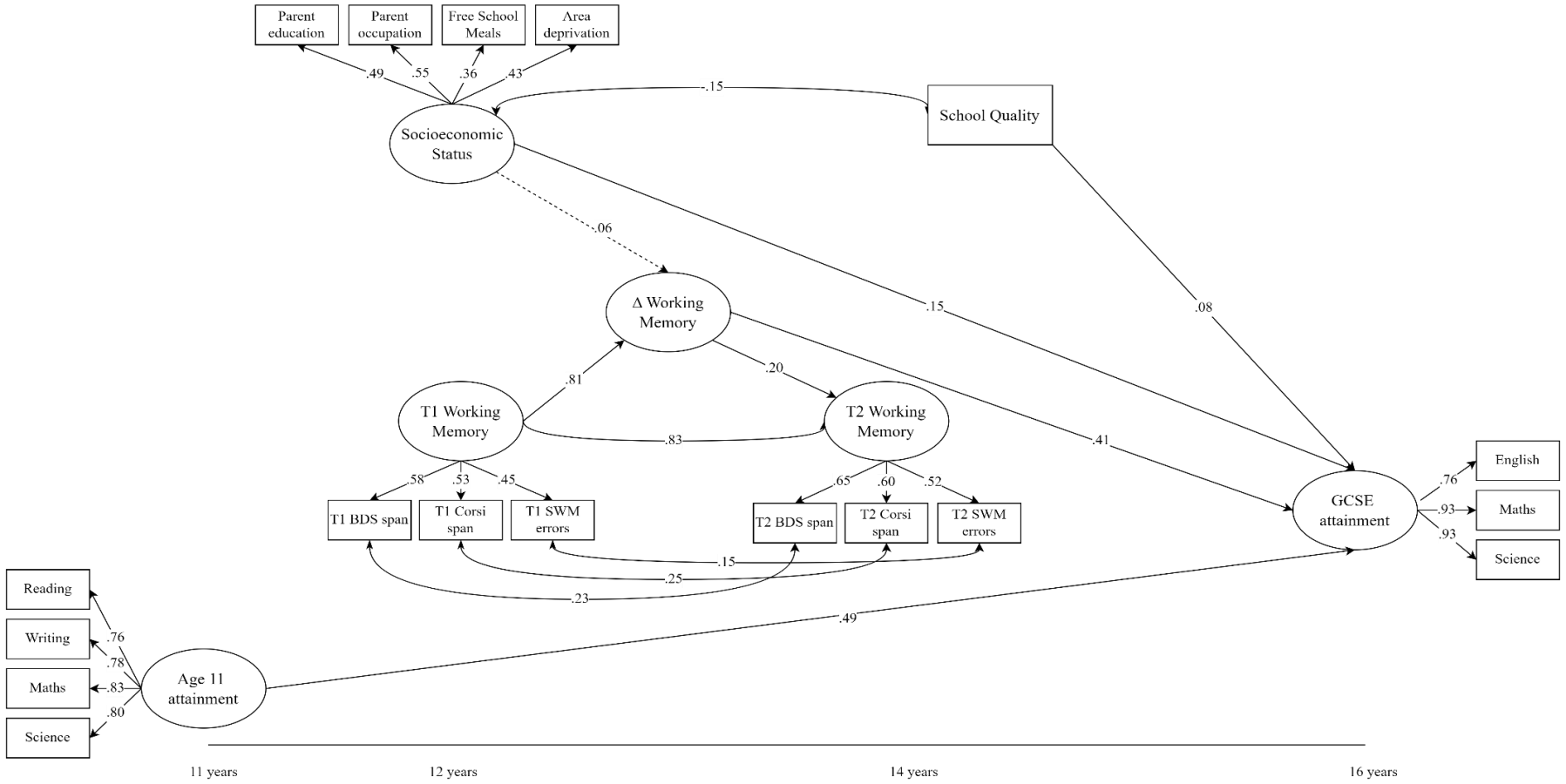
Given the surprising effect of adding Ofsted ratings on the socioeconomic status to working memory association in model 1, I then reran model 2 controlling for Ofsted ratings to check that the socioeconomic status to working memory associations I previously observed were not driven by school effects.

Model fit was within acceptable limits (CFI = .90, RMSEA = .08) and results were very similar to those observed without including this control variable. The model explained 40%, 55% and 46% of the variance in English, maths and science, respectively. Again, paths

from socioeconomic status to attainment were larger with the addition of school quality ratings but less notably in this case and, again, Ofsted rating was a significant predictor of attainment with an effect around half the size of socioeconomic status. Socioeconomic status to working memory associations were negligibly or not reduced in this model and all paths from socioeconomic status to attainment also remained significant. These results are shown in **Figure 4.14**.

Figure 4.13

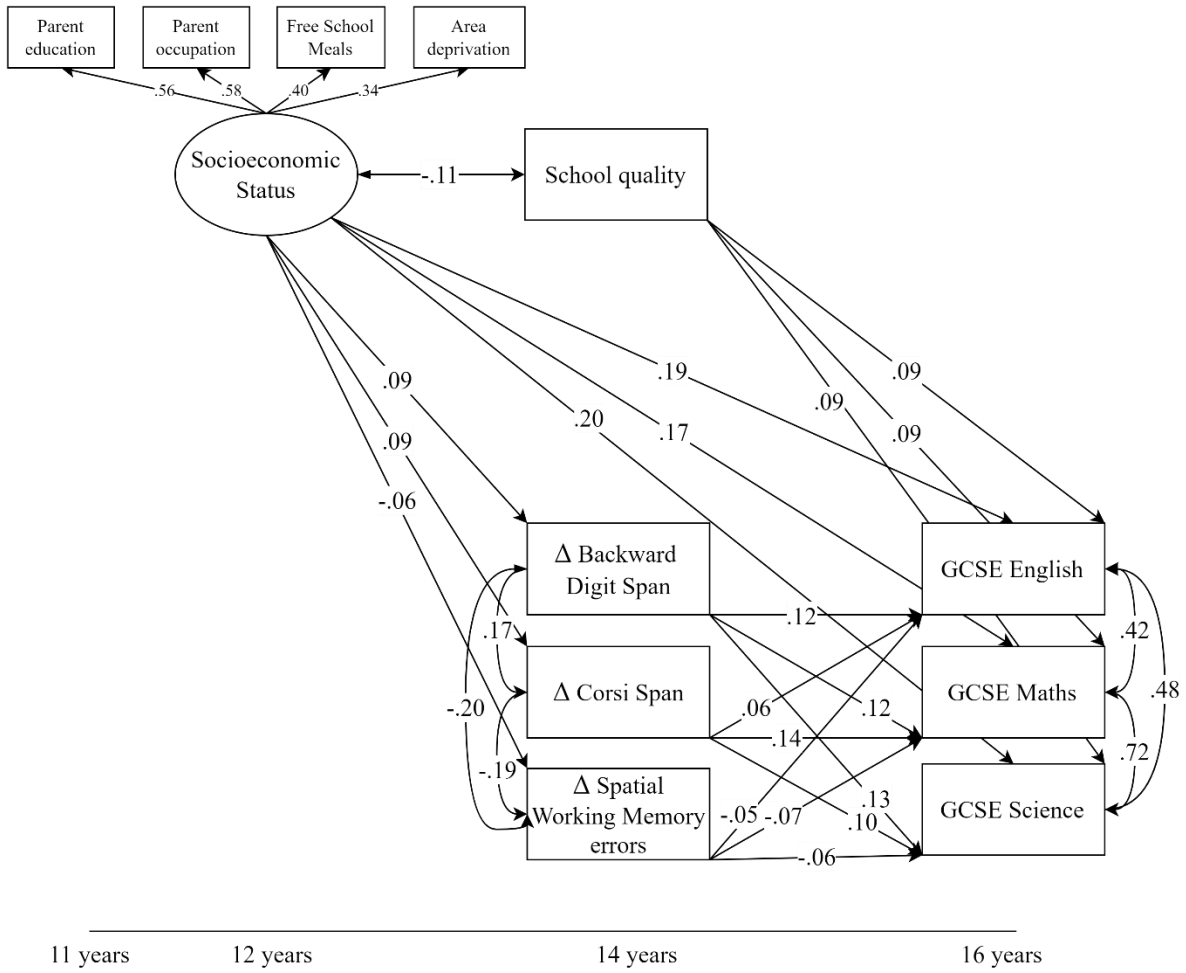
Path diagram showing the beta estimates for the regression paths estimated in model 1 after the inclusion of Ofsted school rating.



Note. Solid paths indicate significant associations at $p < .05$ and dashed paths indicate non-significance.

Figure 4.14

Path diagram showing the beta estimates for the regression paths estimated in model 2 after the inclusion of Ofsted school rating.



4.4 Discussion

4.4.1 Results summary

This study explored the relationship between socioeconomic status, change in working memory over adolescence and change in attainment over adolescence. I observed that an increase in the socioeconomic gradient in attainment over adolescence followed increasing social inequalities in working memory skills in early adolescence. However, this effect was only apparent in models where I treated working memory measures and GCSE

subjects separately and not when I combined them into factors. Unpacking these associations further, I showed that parent occupation and household poverty are related to changes in both working memory and attainment during adolescence. Other aspects of socioeconomic status predicted changes in attainment but not working memory (parent education) or did not predict changes in attainment (area level deprivation). These associations were robust to the inclusion of auxiliary variables.

In a first analysis, I found that change in working memory from 12-14 years, but not a factor of socioeconomic status indices, was a small and significant predictor age 16 attainment (treated as a factor combining standardised English, maths and science assessments), controlling for age 11 attainment. Together, these two predictors explained 75% of the variance in age 16 attainment. The effect of socioeconomic status on attainment at 16 was significant and larger when I controlled for Ofsted ratings of school quality, suggesting that socioeconomic effects were not driven by school effects in this sample as I was initially concerned about. Rather, high quality schooling made up for some of the negative effects of low socioeconomic status on attainment in this sample.

I then looked at whether these observed associations were specific to certain working memory measures or subjects. The models explained most variance in maths (54%) and least in English (40%), partly because maths showed particularly strong longitudinal stability. However, the socioeconomic status factor had slightly stronger links to science and English attainment than to maths attainment. A 1 SD change in score on the socioeconomic status factor (equivalent to an increase from the 50^{th} to the 84^{th} percentile of socioeconomic status) was associated with an increase of up to 30 - 37% of a GCSE grade (these associations were reduced by around a third in models covarying for school type, testing session duration and Free School Meals percentage at the school level). For English, verbal working memory was almost twice as strong a predictor as visuospatial working memory and both were less

strongly tied to attainment than socioeconomic status. The same pattern was seen for science attainment, although the difference between predictors was smaller. However, none of these differences were statistically significant. For age 16 maths, verbal and visuospatial working memory span were as good predictors as socioeconomic status.

It is important to note that these figures described above are not adjusted for ethnicity and first language status and may therefore underestimate social inequalities in outcomes in some groups of pupils and overestimate them in others. The tables in **Chapter 4 Appendices: Appendix B** and **D show** that the relationship between socioeconomic status and GCSE attainment was stronger with the addition of ethnicity and first language status controls, meaning that socioeconomic status effects were stronger in the reference groups (monolingual English-speaking and white/mixed race pupils). This likely explains why model fit was worse when these controls were added. These results are in line with the picture shown by national statistics (GOV.UK, 2023c) and has been taken to suggest that there are factors linked to certain demographic backgrounds that can mitigate against the impact of socioeconomic status on attainment (Stokes et al., 2015). Examples include involvement of the wider family in child rearing, attitudes toward education, and the possible cognitive benefits of learning multiple languages (e.g., Iqbal & Modood, 2022; Filippi et al., 2022; Stokes et al., 2015).

This study also aimed to test whether widening social inequalities in working memory during adolescence predict, and are therefore a possible causal pathway for, widening attainment gaps over adolescence. I therefore ran mediation analysis with 50,000 Montecarlo simulations in my best fitting model. Change in working memory over adolescence was a significant partial mediator of the socioeconomic status-attainment association and explained between 11-17% of the relationship between socioeconomic status and attainment in different subjects. All working memory measures, significantly contributed to explaining the effects of

socioeconomic status on attainment in maths and science but only verbal working memory mediated the socioeconomic status to English attainment relationship.

As a final step in testing specificity of associations, I removed the socioeconomic status factor and included the four socioeconomic status indices as individual predictors to test my prediction that socioeconomic status indices would have separable effects on working memory and attainment. A pupil's number of university educated parents positively predicted their attainment in each of the core subjects at age 16 (over and above age 11 attainment), but not their change in working memory skills from 12-14 years. By contrast Free School Meals (FSM; a proxy for household poverty) negatively predicted performance in English, maths and science at 16, performance on the BDS (a measure of verbal working memory span) and positively predicted SWM errors (a self-ordered measure of visuospatial working memory difficulties). FSM status was not, however predictive of change in my measure of visuospatial working memory span (Corsi span). Parental highest occupation ranking also predicted English and science grades at age 16, but not age 16 maths. This index also predicted change in visuospatial working memory span but not performance on the other two working memory tasks. Area deprivation was not associated with change in performance on any working memory task or any age 16 attainment measures.

4.4.2 Consistency with the wider literature

These results are consistent with Donati et al. (2019) who, in a sample of pupils from the same age group and country but a decade earlier, observed that working memory explains significant variance in age 16 attainment in English, maths and science, controlling for age 11 attainment. I extend these findings to show that changing working memory skills over adolescence are associated with change in attainment in the three core subjects, allowing for stronger inferences of causality. Further, my results replicate Albert et al.'s (2020) finding from a study of middle school pupils that working memory mediates the longitudinal

socioeconomic status-attainment link. Importantly, I observed slightly larger mediation ratios than Albert et al., suggesting that their results were not driven by working memory correlating with earlier attainment (which they did not control for in their models). Together, these findings provide a strong challenge to the Fade Out Hypothesis (Stipek & Valentino, 2015); the importance of working memory skills for school success does not appear to fade away during adolescence. Instead, widening social inequalities in working memory skills partly mediate, consistent with the possibility of this being a causal explanation of, widening attainment gaps during adolescence.

Using a factor combining performance on several different working memory tasks, Donati et al. (2019) found that working memory was more strongly associated with maths attainment than English attainment. Similar results were obtained by Albert et al. (2020). They showed that a measure of verbal working memory significantly predicted both reading and maths attainment, but maths more strongly, and that visuospatial working memory only predicted maths. They also found that verbal working memory was a stronger predictor of maths than was visuospatial working memory and only verbal working memory mediated socioeconomic gaps in reading and maths attainment. Whilst the Corsi (visuospatial working memory) span showed stronger associations with maths than English in the present study, as in Donati et al. (2019) and Albert et al. (2020), differences in the strength of its associations with attainment across subjects were not statistically significant[10]. Further, verbal working memory showed no subject selectivity in the present study and was not a significantly stronger predictor of maths than visuospatial working memory measures. Across subjects, SWM errors was the weakest working memory predictor of attainment, mirroring Jarvis and

[10] Donati et al. (2019) and Albert et al. (2020) did not report on the significance of these differences.

Gathercole's (2003) finding that working memory span tasks tend to be better predictors of achievement in national curriculum tests than other forms of working memory measure.

Whilst I did not find my model looking at specific associations between working memory and attainment fit the data better than the general effects model as in Donati et al. (2019), my specific effects models nevertheless revealed important nuance. First, associations with the socioeconomic status factor were larger for individual subjects than for a factor of the subjects. This suggests that some of the unique aspects of GCSE English, maths and science are related to socioeconomic status in addition to the common skills tapped by the three measures. Second, comparing these two models, we can see that the small association between socioeconomic status and SWM errors likely diluted the larger associations between socioeconomic status and the working memory span measures when I treated working measures as a factor. These results show that grouping executive function or attainment measures can lead to underestimation of the full extent of socioeconomic effects.

This point is reinforced by my results from mediation analysis. I replicated the finding from a previous study of middle schoolers (Albert et al., 2020) that visuospatial working memory does not explain social inequalities in English attainment. However, in contrast to the previous mediation study, change in performance on visuospatial working memory measures did significantly mediate the relationship between socioeconomic status and maths in the SCAMP cohort, as well as the relationship with science. I also replicated Albert et al.'s finding that verbal working memory partly explains the association between socioeconomic status and attainment in maths and English. I extend these findings to show that verbal working memory also partly explains the socioeconomic gradient in secondary school science attainment. Such nuanced findings are valuable for informing intervention targets and would be missed had I grouped together working memory measures and attainment measures in all my analyses.

The results from this study and Albert et al.'s (2020) study converge to suggest a potentially important role for working memory in explaining social inequalities in educational attainment. However, for the SCAMP participants, less than half of the relationship between socioeconomic status and educational attainment was mediated by working memory. This may in part be because I only measured change in working memory over two years out of the five-year gap between assessments. Some of the remaining association may also have been explained by social inequalities in other cognitive skills which were not included in this study. For example, processing speed predicted attainment in Donati et al. (2019) and non-verbal reasoning was more strongly related to socioeconomic status than executive function measures were in in the analyses carried out in **Chapter 3**. Research in young children has additionally shown that language skills explain about 50% of the relationship between socioeconomic status and maths skills (James-Brabham et al., 2023) and my exploratory analyses in the previous study (where I used age 11 attainment scores averaged over reading and writing), as well as the work of Noble et al. (2007), suggest that language skills are more strongly linked to socioeconomic status than executive function is. Future studies may consider looking at measures such as vocabulary or reading comprehensions as mediator of social inequalities in attainment during adolescence.

Other processes at work may be more psychosocial. Research has shown that low socioeconomic status pupils have less confidence in their intelligence and their ability to grow their skills, irrespective of their actual abilities, and that these negative self-views increase with age (Brummelman & Sedikides, 2023). Moreover, it has been suggested that a process of disillusionment with education occurs for low socioeconomic status pupils during adolescence. They are thought to reduce the effort they put in to schoolwork as they become cognisant of socioeconomic status-linked differences in access to opportunities and come to understand the substantial cost of entering into higher education (Caro et al., 2009; Guo,

1998). Relatedly, children in low socioeconomic status families are less likely to have educational aspirations that align with their parents' aspirations for them, and incongruent parent-child aspirations are linked to lower educational attainment (Schoon & Burger, 2022). Another possible factor contributing to social inequalities in attainment may be mental health difficulties. These often onset during adolescence (Jones, 2013), when they are particularly strongly associated with poorer educational outcomes (see Burger et al., 2024 for a comparison of adolescent with young adult educational outcomes), and are 2-3 times more common in low socioeconomic status children and adolescents (Reiss, 2013). Sleep difficulties, which occur more frequently in low socioeconomic status individuals, have additionally been shown to contribute to lower school attainment (Buckhalt, 2011).

Several studies have shown that socioeconomic status gaps in attainment widen over the long summer break (e.g., Alexander et al., 2007; Downey et al., 2004, but also see Hackman et al., 2015 for evidence that socioeconomic gaps do not narrow when children start school) suggesting that schools act as *equalisers*, making up for some of the effects of poverty on attainment. In support of this notion, socioeconomic status effects were stronger when I controlled for school quality. Interestingly, in the SCAMP subsample, school quality had a small but significant negative association with socioeconomic status, explaining why I did not observe a significant association between socioeconomic status and attainment in my first model until I controlled for school quality. However, the results from this model should be interpreted with caution given the limited representation of poorly performing schools in this sample and the mixed evidence regarding compensatory effects of schools (e.g., see Berkowitz, 2021; Canales & Maldonado, 2023).

By contrast, in models where I looked at socioeconomic status and working memory effects on performance in different subjects, I found that age 11 maths was a very strong predictor of maths and science attainment at 16. Its association with science was twice and its

association with maths three times larger than most other age 11 to age 16 attainment associations. These effects are considerably bigger than those observed in the ALSPAC sample (Donati et al., 2019), possibly reflecting a change in the maths curriculum demands and assessments the ALSPAC and SCAMP participants were exposed to as a result of the 10-year age gap between them (see Majewska et al., 2022)[11]. This, and the fact that I looked at change in working memory skills over a 2-year period rather than average working memory skills across adolescence likely explains why I did not replicate Donati et al.'s (2019) finding that working memory is a stronger predictor of age 16 attainment than any age 11 attainment measures.

By looking at the pathways from different socioeconomic status indices to attainment, I provide evidence that takes us closer to a mechanistic understanding as to the ways in which socioeconomic status is related to attainment in adolescents. In this study, parental occupation and household poverty (Free School Meals status) predicted attainment in the three core subjects at GCSE level and change in performance on one or more working memory measure. These results are consistent with Pensiero and Schoon's (2019) and Schoon et al.'s (2021) findings that parental occupation and income related factors have independent effects on educational attainment and cognitive skills. In the present study, these measures were also indirectly related to change in attainment via change in working memory. Following Bukodi and Goldthorpe (2013), these results could suggest that families' sociocultural and economic resources have separable promotive effects on children's cognitive development, with downstream consequences for academic outcomes.

[11]Multiple changes to maths curriculum and teaching strategy were implemented between the time the ALSPAC participants started school and the SCAMP participants finished compulsory schooling. Notably, in 2017 (the year before the oldest SCAMP participants sat their GCSEs), the assessment system was also changed with the introduction of reformed GCSEs.

In the present study, parental occupation was positively associated with change on a measure of visuospatial working memory span and Free School Meals status predicted change in performance on a verbal working memory span task as well as a self-ordered spatial working memory task. It is surprising that the visuospatial tasks did not cluster together. However, there is evidence that children engage in subvocal rehearsal during visuospatial working memory tasks (Poloczek et al., 2019) and this reliance on subvocal rehearsal may be especially prominent in tasks such as the Spatial Working Memory task which involve planning and strategising. Studies have shown that income poverty is related to reductions in brain volume, particularly in cortical regions dealing with language and executive function (see Blair & Raver, 2016; Noble et al., 2015 for reviews). Further the relationships between income poverty and brain volume and activation have been shown to be mediated by experience of chronic stress (Kim et al., 2013; Luby et al., 2013), suggesting a possible mechanism for the observed income poverty effects on these tasks. Research into the mechanisms through which parental occupation (or sociocultural resource) is related to brain and cognitive development is much more lacking, as is research linking socioeconomic status to visuospatial working memory. However, it is known that there are social inequalities in participation in activities thought to benefit visuospatial skills (e.g., playing musical instruments and sports; Pietsch & Jansen, 2012) in the UK (Donnelly et al., 2019), so one possible explanation could be that families with higher sociocultural resources place more importance on participation in these activities.

Parental education, often reported to be the most reliable predictor of academic outcomes and cognitive skills in children (Davis-Kean, 2005; Waters et al., 2021), did not predict change in working memory over adolescence in the current study but did predict age 16 attainment. Its relationship with attainment during adolescence may therefore be explained by factors such as parents' ability to help with schoolwork and academic pressure (e.g.,

Davis-Kean et al., 2019) which are likely to help students succeed academically but have no intuitive link to executive function. However, that well controlled longitudinal studies in children (e.g., Davis-Kean, 2005; Waters et al., 2021) and a cross-sectional analysis of this cohort at age 11 (**Chapter 3**) show significant positive associations between executive function skills and parent education suggests that there may be a developmental change in the importance of this variable for cognitive development but not attainment. More evidence from adolescents is needed to reliably test this prediction. The coming waves of data collection in the Adolescent Brain and Cognitive Development (ABCD; https://abcdstudy.org/) offer a good opportunity to replicate these results.

It should be noted that parent education effects are likely to be weaker in the SCAMP cohort, compared to older datasets. Increasing numbers of adults in the UK hold a first degree (Bolton, 2024), thanks to the student loan system which reduces the financial barrier that historically prevented young people from poorer families from accessing higher education. However, there is a large drop in the number of students who pursue postgraduate education in the UK. Therefore, a measure looking at whether parents were postgraduate educated may have been more sensitive to the effects of parent education on attainment and cognitive skills in the SCAMP cohort and may explain why parental education effects were comparable (or slightly smaller in the case of maths) to household income effects, in contrast to Davis-Kean (2005) and Waters et al. (2021). Such a measure should be employed in future UK studies if less coarse measures of parental education are not possible to take.

In contrast to the other socioeconomic status indices, I observed no direct or indirect effects of area deprivation on attainment in the present study. This is consistent with the conclusion from a systematic review of the literature that area deprivation has smaller effects on attainment than other socioeconomic status indicators (Sirin, 2005). According to research using data from the Longitudinal Study of Young People in England by Mc Dool (2017), the

effects of neighbourhood deprivation on attainment are worse for adolescents with parents educated to post 16 level compared to those whose parents left school before 16. Given the skew of the SCAMP data toward having two highly educated parents, it is therefore surprising that I did not observe significant effects of area deprivation on attainment. However, whilst matching participants on multiple sociodemographic indices (e.g., KS2 attainment, parent education, parental employment), Mc Dool did not control for the effect of household income/poverty on area deprivation. Since this aspect of socioeconomic status is likely to have the strongest association with neighbourhood selection, this may explain the discrepancy between my and Mc Dool's findings. Studies of neighbourhood deprivation and attainment in adolescence typically only account for parent education when trying to remove the confounding effect of family level factors (e.g., McDool, 2017; Nieuwenhuis et al., 2021; Weinberg et al., 2019) and may therefore overlook the complexity of social inequalities in educational attainment.

4.4.3 Practical implications

The findings from this study afford several important implications. First, we should be concerned about widening social inequalities in attainment that occur over adolescence. If the effects observed here followed a linear trajectory, socioeconomic status could explain around a whole grade difference over the 5 years between 11 and 16. These results cannot simply be put down to the aspirations of young people growing up in poverty or the effort they put into their schoolwork, as are sometimes discussed (e.g., Goodman & Gregg, 2010), since nearly a fifth of this effect in individual subjects was predicted by widening gaps in a single executive function over adolescence. My results show that working memory has separable effects on adolescent attainment from prior attainment, suggesting that it may play a causal role in the learning process.

My results further suggest that pupils from deprived families may benefit from being taught memorisation strategies to compensate for their relative working memory difficulties or be encouraged to use working memory aids. In particular, my results suggest that pupils living in poverty and/or pupils with parents with low occupation prestige may benefit from working memory support. However, I urge that interventions specifically focusing on working memory in low socioeconomic status adolescents are likely to do little to level up social inequalities in attainment unless they are very intensive. I observed significant but small effects of changes in working memory skills over a two-year period on change in attainment from 11 to 16 and most working memory training interventions are light touch and last only for a maximum of several months. To see meaningful far transfer effects over a short period of time, a more comprehensive approach that addresses multiple of the factors underpinning the socioeconomic status gradient in attainment is likely to be more effective. I discuss this point in further detail in Perry et al. (in press).

4.4.4 Strengths and limitations

In this study, I demonstrated relationships between socioeconomic status, working memory and attainment that unfold specifically during adolescence. Since I was able to control for prior attainment and working memory skills, these results provide stronger evidence for causal associations between executive function and attainment than has been possible to demonstrate in previous observational studies of adolescents.

A limitation of this study is that I did not have any measures at the teacher or class level. Hence, I was unable to look at factors operating at these levels which might reduce the association of low socioeconomic status or working memory difficulties with lower attainment. For instance, strong teacher-pupil relationships are positively associated with student attainment (Evans & Field, 2020), particularly in low socioeconomic status pupils (Olsen & Huang, 2021). Further, teachers employ a range of strategies to support students

with cognitive difficulties. The extent to which the use of these strategies is reinforced, due to competing demands on the teacher's time and attention, and the appropriateness of the individual strategies could influence the success of their pupils.

The sample of pupils studied were all in mainstream education, meaning that they represent a predominantly neurotypical population. These findings may not apply to neurodivergent pupils who characteristically have much spikier cognitive profiles (e.g., Pulina et al., 2019; Wilson, 2023) and may therefore make use of different cognitive skills (i.e., their relative strengths) in learning and assessment. Meta-analyses by Friso-van den Bos et al. (2013) and Peng et al. (2016) show that the effects of executive function on attainment are generally smaller in typically developing samples (compared to samples of pupils with versus without special educational or socioemotional and mental health needs/disabled pupils in the former review and pupils with mathematical learning difficulties associated with cognitive difficulties in the latter). Future research should investigate the relations between socioeconomic status and attainment in pupils with different neurodevelopmental conditions.

4.4.5 Conclusions

This study has shown that socioeconomic status-related gaps in attainment widen during adolescence and that up to a fifth of this effect can be explained by widening gaps in working memory. Sensitivity checks showed that the association between socioeconomic status and age 16 attainment was not explained by school quality or confounding from ethnicity or first language status. I found little evidence for specific associations between different working memory tasks and performance in standardised exams in different subjects, although span tasks trended toward being better predictors of attainment. However, only verbal working explained some of the attainment gap in English, whilst verbal and visuospatial measures explained social inequalities in maths and science attainment. Further, I observed specificity at the socioeconomic status level: parental education level, parental

occupation, and household poverty, but not area deprivation, were unique predictors of attainment in the core subjects at age 16, whilst only parental occupation and the household income proxy appeared to predict attainment via working memory. These two indices also associated with changing performance in different working memory measures over adolescence.

My results strongly challenge the notion that executive function skills are only important for attainment in primary education and provide an important starting point for understanding different pathways from socioeconomic status to attainment during adolescence. Further research exploring the mechanisms explaining the observed associations in adolescence is needed to help understand how best to support low socioeconomic status pupils to succeed in schools and to prevent the negative consequences of socioeconomic status-related inequalities in attainment.

Chapter 5: Conclusions

This body of work drew upon the lessons learnt from decades of research into developmental relations between socioeconomic status, executive function, and attainment in children to answer questions about the nature of these associations during adolescence. Using data from the Study of Cognition, Adolescents and Mobile Phones (SCAMP) linked with National Pupil Database data, this project offers, to my knowledge, the first evidence of relationships between socioeconomic status, executive function development and attainment during adolescence.

In **Chapter 1**, I linked the limited research done with teenage samples to the overwhelming international focus on the early years as a time for promoting good outcomes for individuals from low socioeconomic status backgrounds. I overviewed the lessons learnt from decades of research looking to understand how socioeconomic status, executive function and attainment are related in younger children which informed the analyses described in **Chapters 3** and **4**. Then, I described the key findings obtained from other cohort studies of adolescents and the limitations of these datasets for informing our understanding of the relationships between socioeconomic status, executive function, and attainment (i.e., old data, a lack of repeated measures of executive function, few socioeconomic status indicators). **Chapter 2** then gave a detailed description of the methodology and analysis strategy.

In Chapter 3, I showed that there is a small but significant widening of the socioeconomic status gradient in executive function skills between the ages of 12-14 years, controlling for demographic factors. Unpacking this association, I found that the widening gap was specific to performance on working memory span tasks. Further, I showed that the effect was driven by a proxy for household income (Free School Meals status) and parent occupation. Interestingly, whilst parent education predicted executive function skills at age 12 (in cross-sectional models), it did not contribute to the widening gap over the proceeding two years. Similarly, performance on a visuospatial working memory span task (and on the

strategy measure also from this task), as well as on an inhibitory control task at age 12 was significantly associated with socioeconomic status. However, the socioeconomic status linked gradient of performance on these tasks showed no widening effect over the study period.

Chapter 4 built on these findings and asked whether the widening social inequalities in performance on national exams that are consistently observed in the UK from age 11 to age 16 can be explained by widening gaps in working memory skills. In line with the national picture (Education Policy Institute, 2023), socioeconomic status predicted age 16 attainment, controlling for age 11 attainment, indicative of widening gaps. Further analysis showed that change in working memory skills from 12-14 also predicted widening gaps in attainment, accounting for socioeconomic status. However, these effects were not apparent when I grouped working memory measures together and attainment measures together. Mediation analysis showed that change in working memory skills from 12-14 years explained between 11-17% of the effect of socioeconomic status on attainment in different subjects.

These analyses further showed that change in verbal working memory over adolescence was an equally good predictor of age 16 attainment across the core subjects and that it explained a portion of the effect of socioeconomic status on each subject. On the other hand, change in visuospatial working memory skills partly mediated the socioeconomic status to attainment link only in maths and science. Key differences between socioeconomic status indicators were also shown. Parent education predicted attainment in each of the three core subjects but not working memory. Meanwhile parent occupation and Free School Meals status predicted attainment across subjects (or most subjects) and change in specific measures of working memory skills over adolescence.

5.1 General reflections

Mousavi et al. (2022) urge caution in extending the findings of research on socioeconomic status outside of the culture that research was conducted in and encourages researchers to explain the unique context in which their participants are located. A peculiarity of the UK is the persistence of a historic class system in influencing how individuals identify themselves (Heath & Bennett, 2023) and how they think about other people (e.g., see Smith, 2017 for the results of a YouGov survey on attitudes toward the working, middle and upper classes). Further social mobility is relatively limited in the UK relative to other high-income countries (Eyles et al., 2022; D'Addio, 2007). These factors may contribute to explaining differences between my results and those obtained in other samples. For example, I did not replicate the pattern seen in much US research that parental education is a particularly strong predictor of cognitive and educational outcomes (e.g., Davis-Kean, 2005; Waters et al., 2021).

The results presented in this thesis could be taken to paint a rather bleak picture about the prospects of individuals who grow up in poverty in the UK. A large body of literature shows that there are social inequalities in executive function and attainment during primary education (e.g., Last et al., 2018; Early et al., 2020) and I showed that socioeconomic status continues to predict attainment in adolescence (partly through working memory development). Further, that I observed increasing gradients in working memory skills and attainment over adolescence could imply an accumulating effect of socioeconomic status on these outcomes over development. However, my results demonstrate that it might be possible to disrupt some of the negative downstream consequences of low socioeconomic status for individual outcomes as late as adolescence. They also suggest that high quality schooling might have small equalising impacts on attainment. It is hoped that these findings inspire further research focused on understanding what we can do to better support low

socioeconomic status adolescents in succeeding academically. Research spanning the whole of adolescence is needed to test whether the pattern of an increasing socioeconomic gradient in attainment persist beyond age 16 and to further our understanding of possible windows of opportunity for intervention.

Research that goes beyond associations to attempt to establish causal relations is also necessary if we are to understand how best to support pupils from low socioeconomic status families. Beyond the limitations of the data and sample reported in **3.4.3** and **4.4.4** which reduce the confidence in the conclusions that can be drawn from these studies, observational studies of the sorts reported here suffer from several limitations which can obscure interpretations of causality. Although I controlled for multiple demographic factors shown to be related to socioeconomic status and cognitive and academic outcomes in my studies, it remains possible that unmeasured confounds may have driven the observed associations. Moreover, the statistical approach taken in this thesis was confirmatory; whilst the models fit the data adequately, there may have been other models that better reflect reality.

It is practically and ethically challenging to conduct intervention studies focused on changing socioeconomic status. The plausibility of causal pathways can instead be assessed by laboratory studies e.g., train executive function and look at the effect on attainment or employ stress reduction interventions and see whether they improve executive function skills. However, the generalisability of laboratory findings to naturalistic populations is always in doubt. Occasionally socioeconomic circumstances change for some individuals in longitudinal studies (e.g., due to parent separation or job loss), allowing us to study the effects of this change on outcomes of interest. However, such data is rare and usually limited to small samples. Hence, mechanistic understanding in this area must be developed based upon convergent methods and plausibility arguments.

My findings revealed that the relationship between socioeconomic status and executive function is nuanced. Socioeconomic status was not related to cognitive flexibility at age 12 or change in cognitive flexibility from 12-14 years and, despite baseline differences in planning and inhibitory control, there was no widening socioeconomic gradient in these skills observed over adolescence. The specificity of the effects of socioeconomic status on change in working memory skills over adolescence is consistent with cognitive adaptation explanations (e.g., Frankenhuis & Nettle, 2020; Mittal et al., 2015) of the effects of socioeconomic status on cognitive development. Cross-sectional research on adults, located within this framework, has shown that individuals who grew up in chaotic environments perform worse than those who grew up in more stable environments on inhibitory control but not cognitive flexibility tasks (Mittal et al., 2015). These results fit with my own cross-sectional findings. Importantly, though, Mittal et al.'s (2015) participants who grew up in unpredictable environments performed better than those from stable home environments on the cognitive flexibility task under stressful conditions (created by first having participants read an article about the economic recession and financial uncertainty). This suggests that testing conditions can affect the extent to which we accurately capture the full cognitive potential of individuals who grow up in difficult circumstances. Further, the degree of similarity between the conditions under which executive function and attainment measures are taken may affect the extent to which the former predicts the latter.

Several recent studies (Miller et al., 2024; Pi-Sunyer et al., 2023) show that adolescents' perceptions of their socioeconomic position predict their socioemotional wellbeing even when controlling for objective or parent reported measures of socioeconomic status. It is unclear whether this trend would translate into cognitive and academic outcomes; this was not possible to investigate in the present studies as no subjective measures of socioeconomic status were collected for the SCAMP sample. However, these findings raise

an important point about the sensitivity of adolescents to social hierarchies. Moreover, some aspects of socioeconomic status may be more readily apparent to one's peers and this may influence the extent to which they predict adolescent outcomes.

5.2 Strengths and limitations

The subsample of the SCAMP cohort included in the present analyses represent a highly ethnically and linguistically diverse group, who are also representative or close to representative of UK figures on several socioeconomic status indices. This is a key strength of the present research, since many studies in this area include samples that do not show meaningful diversity in socioeconomic status (e.g., see Lawson et al., 2018) and results are therefore likely to be generalisable to other English adolescents. However, the results may be more relevant to urban dwelling adolescents since the nature of urban versus rural poverty differs markedly in the UK; difficulty accessing services can be compounded for low socioeconomic status families who live in isolated communities (Shucksmith et al., 2023). Further, evidence from one study suggests that urban versus rural differences might have important consequences for cognitive development: Tine showed that (2014) poor urban children in the US perform worse on working memory tasks than their wealthier peers, with performance relatively consistent across verbal and visuospatial tasks. However, poor urban children showed asymmetrical results, with significantly greater difficulties in visuospatial compared to verbal working memory.

The extent to which my findings can be generalised to other UK cities can also be called into question. As discussed in Chapter 3 (section **3.4.2**), pupils from low socioeconomic status backgrounds growing up in London have been shown to have better educational outcomes than those from other regions of the UK (Farquharson et al., 2022). This effect is thought to be due to better resourcing of schools. The exceptionality of London may mean that my findings underestimate the associations between socioeconomic status and cognitive

and academic outcomes at the population level. Further, this could explain some of the differences between my findings and those from the other comparable study of UK adolescents (Donati et al., 2019). For instance, the associations between working memory and maths attainment in my study were considerably smaller than in Donati et al.'s study. Better resourced schools may be more able to provide additional support to students at risk for academic difficulties (e.g., due to weaknesses in executive function).

Several reviews also show that the time in which socioeconomic status research is carried out can have significant effects on the estimated size of relationships between socioeconomic status and attainment (Liu et al., 2020; Selvitopu & Kaya, 2021). The SCAMP participants completed formal schooling much more recently than the pupils from other comparable studies: they are 8-13 years younger than the participants from the NICHD *Study of Early Child Care and Youth Development* (SECCYD) and 10-13 years younger than the *Avon Longitudinal Study of Parents and Children* (ALSPAC) participants. The participants were therefore exposed to very different economic and political climates growing up, making it difficult to compare the current findings to these studies. For example, SCAMP participants were in pre- or very early primary school during the global financial crisis of 2007-2008, whilst many ALSPAC and SECCYD participants would have completed formal schooling by this point. Likewise, the findings from SCAMP are likely to be difficult to compare to those coming out of the *Adolescent Brain and Cognitive Development* study (ABCD) due to the Covid pandemic occurring whilst ABCD participants were in early secondary education. Such major events reshape the economic climate of a country (Statistica, 2024) and oftentimes, such as in the case of Covid, widen pre-existing social inequalities in outcomes (Anders et al., 2021).

Whilst heritability estimates for attainment and cognitive skills are small (up to 10% for cognitive skills and 16% for educational attainment, e.g., Cheesman et al., 2022; Lee et al.,

2018; Okbay et al., 2022), I cannot overlook the fact that I was unable to separate out environmentally mediated paths from socioeconomic status to executive function and attainment from genetically mediated paths. Relative social class and affluence are often inherited through families across generations (Eyles et al., 2022), resulting in a significant correlation between genetics and socioeconomic status. The extent to which parenting behaviours that positively predict child cognitive skills and attainment and vary in relation to socioeconomic status are driven by socioeconomic status or genetic nurture (e.g., Kong et al., 2018) is therefore difficult to ascertain.

A further question regarding the specificity of my results is raised since we cannot be sure about the extent to which the results are driven by the executive function aspects of the tasks. Executive function tasks, like any cognitive measure, are not pure tests of the skills they intend to measure. They also inevitably tap abilities such as reading and non-verbal reasoning skills. Bignardi et al. (2024) showed that the association between socioeconomic status and performance on a range of cognitive tasks reduced when controlling for IQ across several different cohorts. Similarly, Pluck et al. (2021) found that when language ability was controlled for, the previously significant relationship they observed between socioeconomic status and executive function reduced to non-significance.

Another limitation of the studies presented in this thesis is that I did not have measures of pubertal development available for the SCAMP cohort. Controlling for age at cognitive testing will, to some extent, have reduced the noise created by the effects of pubertal maturation on executive functions development (Chaku & Hoyt, 2019; Chaku et al., 2022; Porter et al., 2024). However, there is significant inter-individual variability in the age at which puberty onsets and progresses, as well as a reliable difference in the typical age of onset for males and females (Marceau et al., 2011; Susman et al., 2010). Notably, low socioeconomic status is linked to an earlier onset of puberty, accelerated brain maturation

(Thijssen et al., 2020 and see Demidenko et al., 2022 for a robust replication) and greater likelihood of executive function difficulties than one's same age peers (Chaku et al., 2022). Pubertal timing may, therefore, provide mechanistic explanation of my observed effects.

Additional noise in the data may have been introduced by my lack of ability to control for household composition. The education level of parents not cohabiting with their children is likely to have less of an impact on their development than income related metrics (due to them being obligated to pay for child support but not to spend time with their child). Therefore, the inclusion of adolescents from single parent families without any indicator of single parenthood, may have diluted the effect of the pupils' number of university educated parents on executive function and attainment. The separable household income and parental occupation effects I observed in this cohort may be explained by the former tapping family composition. Future studies should test whether these results replicate, controlling for an indicator of family composition.

Another reason why lacking an indicator of family composition is problematic is because single parenthood is much more common in low socioeconomic status families in the UK (Dixon et al., 2023). It has been shown that children from low socioeconomic status single parent families perform worse on executive function measures compared to children from intact but similarly low socioeconomic status families (Sarsour et al., 2011), suggesting that these factors might interact to predict cognitive outcomes. In addition, research conducted by the Higher Education Statistics Agency (Bye et al., 2023), suggests that individuals from single parent families often do not report information about their non-cohabiting parents' educational qualifications. This is likely to apply to other socioeconomic metrics specific to individual patents and may have introduced bias into my data.

On a related note, the accuracy of the parental education and occupation variables may have been lower than my other socioeconomic status indices. These variables come from the direct self-reports of the adolescents in the study who may have felt uncomfortable disclosing this information about their families, since testing took place with other pupils in the room. In some cases, participants from lower socioeconomic status backgrounds may, therefore, have misreported or chosen not to report this information. This may partly explain why the correlation between parental education and occupation was greater than the correlations of these variables with area deprivation and Free School Meals status (**Table 3.2**) and calls into question the comparability of these measures.

5.3 Directions for future research

A priority of future research in this area should be to test mechanistic explanations of the observed associations. Specifically, research is needed to understand how parent occupation and Free School Meals status are related to working memory in UK adolescents to first establish whether these associations are causal and, if so, to then disrupt the chain from low household monetary resources and/or status to working memory difficulties suggested by my findings. Prevention is typically better than cure and a large body of research shows that is notoriously difficult to create improvements in working memory skills via intervention that transfer to educational outcomes (Sala & Gobet, 2017). However, both financial stress (Mistry & Elenbaas, 2021) and access to enriching resources and opportunities (Davis-Kean et al., 2019) could explain my results so further investigation is needed to disentangle the relative importance of these two factors for cognitive and academic outcomes.

Further studies should also focus on identifying what it is about having two university educated parents that is driving the association with higher attainment in UK adolescents. Wertz et al. (2023) offer some possible mechanisms. They showed that the genes associated with educational attainment in mothers are also associated with a number of parenting

behaviours likely to promote better educational outcomes in their children including engaging in cognitive stimulating activities, adopting a health-oriented and structured parenting style and support with schoolwork. Education polygenic scores were also linked to a higher likelihood of breastfeeding and more positive health behaviours during pregnancy which could have effects on cognition that unfold later in development. The results presented in this thesis together with those reported elsewhere (Davis-Kean, 2005; Waters et al., 2021) strongly suggest that the parental education pathway to child attainment operates through quite different mechanisms to the pathways from household income/parental occupation to attainment. However, these studies tend to show that parental education is linked to executive function. The limited heterogeneity in parental education in the present study makes it difficult to confidently conclude the contrary. My results need replicating in a UK dataset which represents a greater diversity in parent education levels.

Further research is likely to benefit from taking an intersectional perspective, given the increased importance of social relationships and identity during adolescence (LaFontana & Cillessen, 2010; Silk et al., 2012). Indeed, social status has been shown to positively predict school attainment in adolescence via emotional distress and studying habits (Destin et al., 2012). Multiple studies have looked at factors predicting attainment at the intersection between socioeconomic status and ethnicity (e.g., Davis et al., 2016; Davis-Kean & Sexton, 2009), but this has mostly been limited to younger pupils. Research is also beginning to look at socioeconomic status as a predictor of individual differences in behavioural outcomes in the context of neurodiversity. For example, in an autism enriched cohort, I have shown that maternal education level predicts stable individual differences in motor, language and perceptual skills (Perry et al., under review). However, research at the intersection between socioeconomic status and neurodiversity is rarely focused on adolescents or located in the context of school outcomes. Future research should expand these areas of study into the

context of understanding social inequalities in cognitive development and attainment in adolescence. A small-scale follow up of the present studies with the autistic pupils in SCAMP (n = 45) is planned.

It will be interesting to see the extent to which the results described in this thesis, based on data from a cohort spanning 2014 to 2018, replicate in the present day. At the time of writing this conclusion, the *cost-of-living crisis* is compounding the difficulties faced by already struggling families (McRae & Westwater, 2023). Further, the recent Covid pandemic disrupted several years of learning for school aged pupils and the livelihoods of children and young people globally, with greatest negative effects seen in the poorest pupils in the US and UK (Betthäuser et al., 2023). Therefore, socioeconomic status effects on educational attainment in the 2020s are likely to be more pronounced than those observed in the SCAMP cohort. My postdoctoral research will examine whether the pandemic amplified social inequalities in attainment in adolescents in France, a country with one of the largest achievement gaps between the richest and poorest students of all PISA participating countries (OECD, 2018).

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Covid impact Appendix

Appendix A

The below document specifies the proposed analyses associated with my Bloomsbury Colleges studentship.

The Approved Research

This information concerns the research outline of the Bloomsbury Colleges funded PhD studentship to link SCAMP cognitive and questionnaire data to educational outcomes, to be carried out at Birkbeck, co-supervised by Prof. Michael Thomas and Prof. Andrew Tolmie (UCL Institute of Education), with a start date of 1st October 2020.

The anticipated educational outcome data from the DfE should comprise GCSE results, school internal measures of Key stage 1 (5-7 years), Key stage 2 (7-11 years), Year 7, and Key stage 3 (11-14 years) academic achievement, as well as per pupil information on SEN and on school attendance as a proxy measure for engagement.

The SCAMP data requested comprise Time 1 and Time 2 cognitive measures (TMT, SWM, BDS, CORSI, CPT), and derived composite measures (principal components of executive function scores), IQ (CFT), SDQ, age, sex, and SES (mother/father education, mother/father occupation, postcode deprivation, state/independent school), along with questionnaire data on technology use and health behaviours (alcohol, drugs, diet, sleep). Data access is requested for 5 years, to include the 4-

year duration of the PhD (3 years of funding + 1 year of thesis write up) and 1 year for publishing papers.

Research questions

Paper 1

Does technology use negatively predict educational outcomes, and is the association mediated by distractibility?

Paper 2

Does use of smart phones positively associate with higher academic achievement, and is the association mediated by improvements in working memory, inhibitory control, visuo-spatial attention, or non-verbal reasoning?

Paper 3

Are early executive function skills a direct predictor of educational outcomes? Is this a general effect or specific to particular educational outcomes? Which tests are most sensitive, and therefore capable of providing a basis to identify children who need extra help?

Paper 4

Do early executive function skills predict eventual educational outcomes via an intermediate association to health behaviours (alcohol, drugs, diet, sleep)?

Analyses

0. Education data clean-up and preliminary analyses

Education data will be cleaned up and linked to existing SCAMP cognitive, technology use, and health measures; preliminary frequency distributions and correlation matrices will be derived.

1. For paper 1: structural equation model predicting GCSE results from technology use with direct pathways and EF measures (most specifically CPT, measuring distractibility) as indirect pathways mediating any relationship. Earlier educational measures, sex, SES, SEN status, engagement, as possible control measures.

2. For paper 2: structural equation model relating technology use T1 to T2 to GCSE results, distinguishing pathways of type of technology use: those offering potential cognitive enhancement or study aids would be predicted to be positively contributing pathways; those encourage displacement would be predicted to be negatively contributing pathways.

3. For paper 3: structural equation model predicting GCSE results from early executive function measures (T1), or EF trajectories (T2-T1). Earlier educational measures, sex, SES, SEN status, engagement, as possible control measures.

4. For paper 4: Analysis as per paper 3, but focusing on T1 EF measures and employing T2 health measures (alcohol, drugs, diet, sleep) as possible mediating pathways to GCSE educational outcome results.

Chapter 2 Appendix

Appendix A

The below document is a copy of the data sharing agreement drawn up between Imperial College London and Birkbeck College.

DATA SHARING AGREEMENT (PSEUDONYMISED CLINICAL DATASET)

between

Imperial College of Science Technology and Medicine, a charitable body registered in England and Wales under registration number RC00231, incorporated under Royal Charter and having its main administrative offices at Exhibition Road, London, SW7 2AZ, United Kingdom (the "Provider Institution")

and

Birkbeck College, University of London, having its main administrative offices at Malet Street, London WC1E 7HX ("Recipient Institution")

hereinafter referred to as "the Parties" and each of them being "a Party"

BACKGROUND

The Recipient Institution is conducting a research project entitled "The relationship between executive function skills, technology use, and educational outcomes in a cohort of 6,000 UK adolescents" as described in more detail at Schedule 1 (the "Approved Research") under the direction of Professor Michael Thomas ("the Recipient Scientist") and wishes to access and use the data specified in Schedule 2 (the "Data") for the purpose of the Approved Research.

The Provider Institution is willing to supply the Data to the Recipient Institution and the Recipient Institution is willing to receive, use, store and dispose of the Data in accordance with the terms and conditions contained within this agreement (the "Agreement").

The Recipient Institution acknowledges the Data has been collected by the Provider Institution under study entitled "Secondary School Cohort Study of Mobile Phone Use and Neurocognitive and Behavioural Outcomes" Reference NIHR 091/0212 funded by the Secretary of State for Health ("Funder").

TERMS AND CONDITIONS

It is hereby agreed as follows:

In this Agreement:

the term “Data” includes Manipulated Data;

the term “Manipulated Data” means any Data that:

the Recipient Institution adapts or combines or aggregates (wholly or in part) with any other data or information (but does not include that other data or information); and which

has not been manipulated by the Recipient Institution to such a degree that it can no longer be identified as originating from the Data nor used as a substitute for the Data; and

the term “Approved Research” includes the publication (if any) of the results of the Approved Research by the Recipient Institution in accordance with clause 0;

the terms “personal data”, “controller”, “processes”, “processing” and “processed” shall have the meanings given in the Data Protection Laws;

“Data Protection Laws” means the Data Protection Act 2018 as amended from time to time and any successor legislation in the UK, and (for so long as and to the extent that the law of the European Union has legal effect in the UK) the General Data Protection Regulation (EU) 2016/679 (“GDPR”) and any other directly applicable European Union regulation relating to data protection and privacy.

In consideration of the obligations accepted by the Recipient Institution under this Agreement, the Provider Institution grants to the Recipient Institution for the term of this Agreement set out in clause 14 a non-exclusive, personal and non-transferable licence to use the Data for the Approved Research. The Provider Institution shall use reasonable endeavours to ensure that it does not share or provide access to any Data under this licence (a) in breach of any legal or contractual obligation or restriction that it is subject to or (b) contrary to the terms of any favourable ethical opinion that relates to the Data.

The Recipient Institution undertakes to the Provider Institution:

to use the Data solely for the Approved Research;

to restrict access to the Data to the Recipient Scientist and those staff and students comprising the Recipient Scientist's research team, and to ensure that those staff and students are aware of and comply with the terms of this Agreement;

to keep the Data confidential and not sub-license, transfer, disclose or otherwise make available the Data in whole or part to any third party except as permitted by this Agreement, without specific prior written consent from the Provider Institution;

to keep the Data secure by implementing organisational and technological measures appropriate to the nature and sensitivity of the data to prevent the unauthorised or accidental access, use or disclosure of the Data including (without limitation) the measures set out in clause 0;

to notify the Provider Institution as soon as reasonably practicable after becoming aware of any unauthorised or accidental access, use or disclosure of the Data, and to co-operate with any investigation made by the Provider Institution in connection with the unauthorised or accidental access, use or disclosure of the Data;

not attempt to re-identify any individual from the Data or communicate with any individual re-identified from the Data, nor to link or attempt to link the Data to other data or information except as described in the Approved Research or with specific prior written consent from the Provider Institution;

to process the Data in accordance with all applicable laws and regulations and any regulator's code(s) of practice applicable to the Data;

to delete all copies of the Data from its hard drives and movable media and destroy all physical copies of the Data as soon as reasonably practicable on completion of the Approved Research or on termination of this Agreement (if earlier), except to the extent the Recipient Institution is required by law to store the Data. This obligation does not extend to automatically generated computer back-up or archival copies generated in the ordinary course of the Recipient Institution's information systems procedures, provided that the Recipient Institution makes no further use of those copies.

to return Data to Provider Institution as soon as reasonably practicable on completion of the Approved Research or on termination of this Agreement (if earlier).

The Recipient Institution shall not make physical or electronic copies of the Data except to the extent reasonably necessary for the Approved Research and shall ensure that any copy of the Data stored on movable media (including laptops) is password-protected and fully encrypted and that any copy of the Data stored on networked or non-networked hard drives is properly protected with firewall and controlled access permissions. The Recipient Institution shall keep a record of where each copy of the Data is stored and shall provide the Provider Institution with a copy of this record on request.

The Data is supplied by the Provider Institution in pseudonymised form without the pseudonymisation key or other means for the Recipient Institution to re-identify individuals from the Data. The Parties anticipate that the Data is likely to be personal data in respect of the Provider Institution's processing but not likely to be personal data in respect of the Recipient Institution's processing, but that this is a question of fact determined by the nature of the Data, the arrangements between the Parties, and any other means available to the Recipient Institution (whether publicly available or otherwise) to re-identify individuals form the Data. In the event that the Data is or becomes personal data when held or processed by the Recipient Institution, the Parties agree that:

each of them shall be a separate and independent controller in respect of its own processing of the Data in connection with this Agreement, and shall be solely responsible and liable for its own processing of the Data including (without limitation) the lawful basis for that processing and ensuring that the Data is processed in compliance with the Data Protection Laws; however

if the Parties are deemed to be joint controllers in relation to the Data, the Parties shall be jointly responsible and liable for the processing of the Data in connection with this Agreement and shall co-operate to determine their respective responsibilities for compliance with their obligations and duties under the Data Protection Laws, including documenting details of this arrangement to demonstrate compliance with Article 26 of the GDPR.

Except to the extent prohibited by law, the Recipient Institution assumes all direct liability for damages which may arise from its receipt, use, storage or disposal of the Data. The Provider Institution will not be liable to the Recipient Institution for any use made, storage or disposal of the Data, including any loss, claim or demand made by

the Recipient Institution or made against the Recipient Institution by a third party, due to or arising from the use, storage or disposal of the Data by the Recipient Institution, except to the extent permitted by law when caused by the gross negligence or wilful misconduct of the Provider Institution.

The Provider Institution provides the Data ‘as is’ and makes no representation and gives no warranty of any kind, either express or implied, including but not limited to warranties of accuracy or fitness for a particular purpose, or that the use of the Data will not infringe any patent, copyright, trademark or other proprietary rights. Trial data is often contributed by third parties and cannot be guaranteed to be free from errors, omissions or inaccuracies, accordingly the Provider Institution will not be liable to the Recipient Institution for any loss, damage, claim or liability arising from any reliance placed on the Data by the Recipient Institution.

Nothing in this Agreement limits or excludes either party’s liability for (a) death or personal injury resulting from negligence; or (b) any fraud or for any sort of other liability which, by law, cannot be limited or excluded.

The liability of either Party for any breach of this Agreement, or arising in any other way out of the subject matter of this Agreement, will not extend to loss of business, or profit, or to any indirect or consequential damages or losses.

The Data is provided and the Approved Research is undertaken in pursuit of the primary charitable objectives of the Parties; that is the advancement of education through research and teaching. The Provider Institution acknowledges that the results of the Approved Research shall belong to the Recipient Institution (except that the Provider Institution retains ownership of the Data to the extent incorporated or included within the results), and that the Recipient Institution is entitled to publish the results of the Approved Research. The Recipient Institution grants to the Provider Institution a non-exclusive, non-transferable, non-sub-licensable, royalty-free licence to use the results for academic and non-commercial research purposes. Any publications reporting on the results of the Research must include the authorship of both parties and seek the approval from and acknowledge the Funder that funded the collection and compilation of the Data, in the form specified by the Provider Institution. The Recipient Institution shall provide a copy of such publication to the Provider Institution thirty (30) days in advance of submission for publication, to allow the Provider Institution (as sponsor of the original study under which the Data were collected) an opportunity to comment on the publication. The Provider Institution agrees not to disclose any results contained in such advance copy to any third party until published by the Recipient Institution. The Recipient Institution shall not publish any confidential or proprietary information belonging to the Provider Institution without its prior written consent, including the Data in whole or in part.

Confidential and proprietary information shall be deemed to include information which was described as such at the point of disclosure and/or was marked as either “confidential” or “proprietary”. The confidentiality obligations in this clause shall not apply where the confidential or proprietary information:

has become public knowledge, other than through an unauthorised disclosure by the Recipient Institution;

was already known to the Recipient Institution, prior to disclosure by the Provider Institution;

was disclosed to the Recipient Institution or the Recipient Scientist by a third party, whom to the Recipient Institution’s knowledge, was not under any obligation of confidence to the Provider Institution;

was released from confidential status by written authorisation of the Provider Institution; or

is required to be disclosed by law or by requirement of a regulatory body or court order.

Notwithstanding clause 10 above, the Provider Institution agrees that nothing in this Agreement shall prevent a student researcher under the direction of the Recipient Scientist from submitting an academic thesis based on the results of the Approved Research for a postgraduate research degree, and/or from the examination of the thesis by examiners appointed by the applicable degree-awarding institution (whether the Recipient Institution or otherwise) in accordance with its standard terms for such appointments (which for the avoidance of doubt shall include appropriate undertakings of confidentiality); and/or from the deposit of the thesis in any library in accordance with such degree-awarding institution’s relevant procedures, which shall include the provision of facilities restricting public access to the thesis in order to safeguard intellectual property rights.

Nothing in this Agreement grants the Recipient Institution any rights over the Data or under any patents, nor any right to use, or permit the use of, any products or processes containing the Data for any profit-making or commercial purposes (“Commercial Use”). Should the Recipient Institution wish to make Commercial Use of the Data and should the Provider Institution be willing and able to grant a licence

for such purposes, the Parties shall negotiate in good faith to agree an appropriate licence or revenue sharing agreement on fair and reasonable terms.

Nothing in this Agreement shall prevent or impede the Provider Institution from being able to use the Data for any purpose, including but not limited to sharing and licensing of the Data to third parties, whether public, private or third sector, for any purpose.

The rights and obligations of the Parties are personal and may not be assigned at any time without the prior written consent of the other Party which consent shall not be unreasonably withheld; provided that it shall be a requirement in all cases of assignation that the assignee undertakes to perform all outstanding obligations of the assignor as though the assignee had been an original party hereto.

This Agreement shall be effective from 01 September 2021 and shall continue in force until 30 September 2025 The term of this Agreement may be extended by the mutual written agreement of both Parties signed by their authorised signatories.

Either Party may terminate this Agreement if the other Party is in breach of any of the terms of this Agreement and, where the breach is capable of remedy, the breaching Party has failed to remedy the same within twenty-eight (28) calendar days of service of a written notice from the from the non-breaching Party specifying the breach and requiring it to be remedied.

Any provision of this agreement that expressly or by implication is intended to come into or continue in force on or after termination of this Agreement, including the Recipient Institution’s obligations under sub-clause 00, shall remain in full force and effect.

The Parties shall procure that in carrying out their obligations under this Agreement, they will comply with all applicable laws, regulations and statutes, including those relating to modern slavery and anti-bribery and the Data Protection Laws. Non-compliance with this clause by a Party shall not be sufficient justification for another Party not to comply with its obligations under this Agreement.

A person who is not a party to this Agreement shall not have any rights under or in connection with it.

Notices

The Provider Institution's representative for the purpose of receiving notices shall until further notice be:

REDACTED

This Agreement constitutes the entire agreement between the parties in respect of its subject matter and no statements or representations made by any Party have been relied upon by the other in entering into this Agreement.

This Agreement shall be governed and construed in accordance with the laws of England and Wales and the Parties agree to the exclusive jurisdiction of the English Courts.

This Agreement may be executed in one (1) or more counterparts, each of which shall be deemed an original, but all of which together shall constitute one and the same instrument. A signed copy of this Agreement delivered by e-mailed portable document format file or other means of electronic transmission shall be deemed to have the same legal effect as delivery of an original signed copy of this Agreement.

Appendix B

Expected knowledge in maths by the end of KS2. Reproduced with permission from Department for Education (Department for Education, 2013c).

Strand	Statutory requirements
Number – number and place value	● read, write, order and compare numbers up to 10 000 000 and determine the value of each digit ● count forwards or backwards in steps of powers of 10 for any given number up to 1,000,000 ● interpret negative numbers in context, count forwards and backwards with positive and negative whole numbers, including through zero ● round any whole number to a required degree of accuracy ● use negative numbers in context, and calculate intervals across zero ● solve number and practical problems that involve all of the above ● read Roman numerals to 1000 (M) and recognise years written in Roman numerals
Number – addition, subtraction, multiplication and division	● add and subtract whole numbers with more than 4 digits, including using formal written methods (columnar addition and subtraction) ● multiply multi-digit numbers up to 4 digits by a two-digit whole number using the formal written method of long multiplication ● divide numbers up to 4 digits by a two-digit whole number using the formal written method of long division, and interpret remainders as whole number remainders, fractions, or by rounding, as appropriate for the context ● divide numbers up to 4 digits by a two-digit number using the formal written method of short division where appropriate, interpreting remainders according to the context ● perform mental calculations, including with mixed operations and large numbers ● identify common factors, common multiples and prime numbers ● use their knowledge of the order of operations to carry out calculations involving the four operations ● solve addition and subtraction multi-step problems in contexts, deciding which operations and methods to use and why ● recognise and use square numbers and cube numbers, and the notation for squared and cubed ● solve problems involving addition, subtraction, multiplication and division ● use estimation to check answers to calculations and determine, in the context of a problem, an appropriate degree of accuracy
Number – fractions (including decimals and percentages)	● use common factors to simplify fractions; use common multiples to express fractions in the same denomination ● compare and order fractions, including fractions > 1 ● add and subtract fractions with different denominators and mixed numbers, using the concept of equivalent fractions ● multiply simple pairs of proper fractions, writing the answer in its simplest form ● divide proper fractions by whole numbers ● associate a fraction with division and calculate decimal fraction equivalents ● identify the value of each digit in numbers given to three decimal places and multiply and divide numbers by 10, 100 and 1000 giving answers up to three decimal places ● multiply one-digit numbers with up to two decimal places by whole numbers ● use written division methods in cases where the answer has up to two decimal places ● solve problems which require answers to be rounded to specified degrees of accuracy ● recall and use equivalences between simple fractions, decimals and percentages, including in different contexts.

Ratio and proportion	● solve problems involving the relative sizes of two quantities where missing values can be found by using integer multiplication and division facts ● solve problems involving the calculation of percentages and the use of percentages for comparison ● solve problems involving similar shapes where the scale factor is known or can be found ● solve problems involving unequal sharing and grouping using knowledge of fractions and multiples.
Algebra	● use simple formulae ● generate and describe linear number sequences ● express missing number problems algebraically ● find pairs of numbers that satisfy an equation with two unknowns ● enumerate possibilities of combinations of two variables.
Measurement	● solve problems involving the calculation and conversion of units of measure, using decimal notation up to three decimal places where appropriate ● use, read, write and convert between standard units, converting measurements of length, mass, volume and time from a smaller unit of measure to a larger unit, and vice versa, using decimal notation to up to three decimal places ● convert between different units of metric measure (for example, kilometre and metre; centimetre and metre; centimetre and millimetre; gram and kilogram; litre and millilitre) ● understand and use approximate equivalences between metric units and common imperial units such as inches, pounds and pints ● measure and calculate the perimeter of composite rectilinear shapes in centimetres and metres ● calculate and compare the area of rectangles (including squares), and including using standard units, square centimetres and square metres and estimate the area of irregular shapes ● recognise that shapes with the same areas can have different perimeters and vice versa ● recognise when it is possible to use formulae for area and volume of shapes ● calculate the area of parallelograms and triangles ● calculate, estimate and compare volume of cubes and cuboids using standard units, including cubic centimetres (cm3) and cubic metres (m3), and extending to other units ● estimate volume and capacity ● solve problems involving converting between units of time ● use all four operations to solve problems involving measure using decimal notation, including scaling
Geometry – properties of shapes	● draw 2-D shapes using given dimensions and angles ● recognise, describe and build simple 3-D shapes, including making nets ● know angles are measured in degrees: estimate and compare acute, obtuse and reflex angles ● draw given angles, and measure them in degrees ● compare and classify geometric shapes based on their properties and sizes and find unknown angles in any triangles, quadrilaterals, and regular polygons ● distinguish between regular and irregular polygons based on reasoning about equal sides and angles ● illustrate and name parts of circles, including radius, diameter and circumference and know that the diameter is twice the radius ● recognise angles where they meet at a point, are on a straight line, or are vertically opposite, and find missing angles.
Geometry – position and direction	● describe positions on the full coordinate grid (all four quadrants) ● draw and translate simple shapes on the coordinate plane, and reflect them in the axes.

Statistics	● solve comparison, sum and difference problems using information presented in a line graph ● complete, read and interpret information in tables, including timetables ● interpret and construct pie charts and line graphs and use these to solve problems ● calculate and interpret the mean as an average.

Appendix C

Expected knowledge in science by the end of KS2. Reproduced with permission from Department for Education (Department for Education, 2013c).

Strand	Statutory requirements
Living things and their habitats	● describe the differences in the life cycles of a mammal, an amphibian, an insect and a bird ● describe the life process of reproduction in some plants and animals ● describe how living things are classified into broad groups according to common observable characteristics and based on similarities and differences, including microorganisms, plants and animals. ● give reasons for classifying plants and animals based on specific characteristics.
Animals including humans	● describe the changes as humans develop to old age ● identify and name the main parts of the human circulatory system, and describe the functions of the heart, blood vessels and blood ● recognise the impact of diet, exercise, drugs and lifestyle on the way their bodies function ● describe the ways in which nutrients and water are transported within animals, including humans.
Properties and changes of materials	● compare and group together everyday materials on the basis of their properties, including their hardness, solubility, transparency, conductivity (electrical and thermal), and response to magnets ● know that some materials will dissolve in liquid to form a solution, and describe how to recover a substance from a solution ● use knowledge of solids, liquids and gases to decide how mixtures might be separated, including through filtering, sieving and evaporating ● give reasons, based on evidence from comparative and fair tests, for the particular uses of everyday materials, including metals, wood and plastic ● demonstrate that dissolving, mixing and changes of state are reversible changes ● explain that some changes result in the formation of new materials, and that this kind of change is not usually reversible, including changes associated with burning and the action of acid on bicarbonate of soda.
Earth and space	● describe the movement of the Earth, and other planets, relative to the Sun in the solar system ● describe the movement of the Moon relative to the Earth ● describe the Sun, Earth and Moon as approximately spherical bodies ● use the idea of the Earth's rotation to explain day and night and the apparent movement of the sun across the sky
Forces	● explain that unsupported objects fall towards the Earth because of the force of gravity acting between the Earth and the falling object ● identify the effects of air resistance, water resistance and friction, that act between moving surfaces ● recognise that some mechanisms, including levers, pulleys and gears, allow a smaller force to have a greater effect
Evolution and inheritance	● recognise that living things have changed over time and that fossils provide information about living things that inhabited the Earth millions of years ago ● recognise that living things produce offspring of the same kind, but normally offspring vary and are not identical to their parents

	● identify how animals and plants are adapted to suit their environment in different ways and that adaptation may lead to evolution.
Light	● recognise that light appears to travel in straight lines ● use the idea that light travels in straight lines to explain that objects are seen because they give out or reflect light into the eye ● explain that we see things because light travels from light sources to our eyes or from light sources to objects and then to our eyes ● use the idea that light travels in straight lines to explain why shadows have the same shape as the objects that cast them.
Electricity	● associate the brightness of a lamp or the volume of a buzzer with the number and voltage of cells used in the circuit ● compare and give reasons for variations in how components function, including the brightness of bulbs, the loudness of buzzers and the on/off position of switches ● use recognised symbols when representing a simple circuit in a diagram.

Appendix D

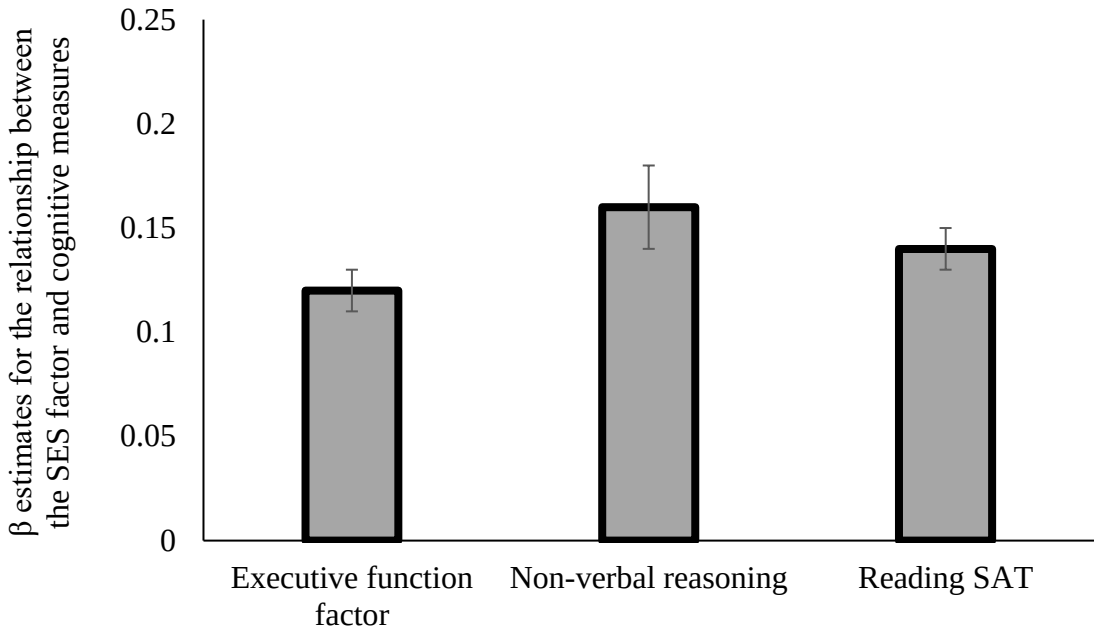
The two possible presentation sequences of the cognitive and demographic measures.

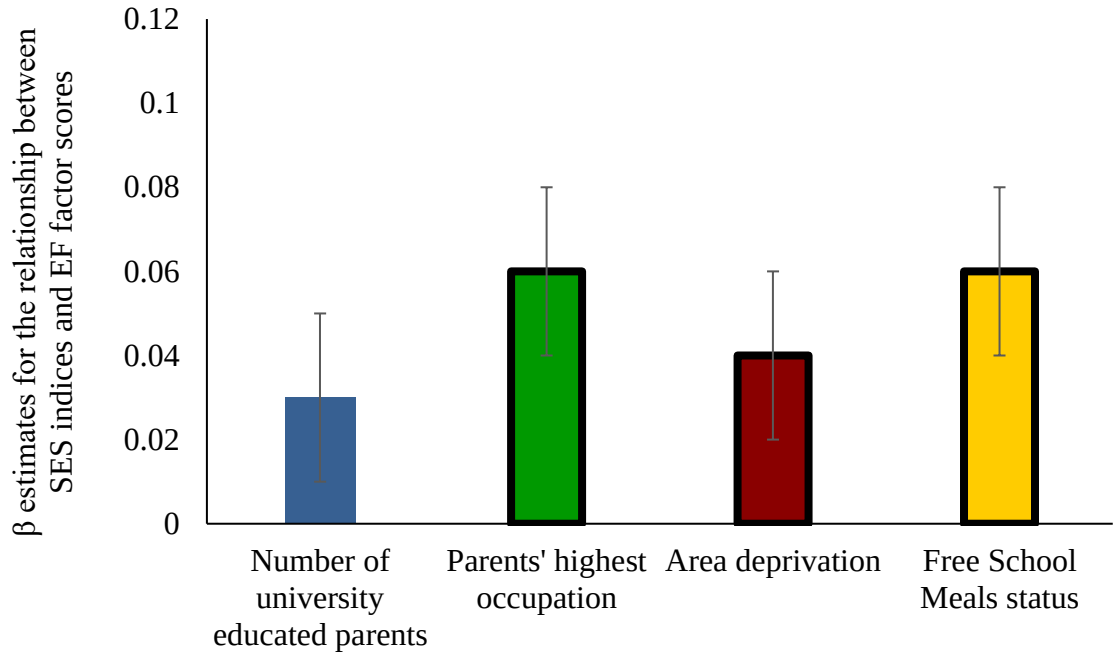
Original order 1	**New order 1**	**New order 2**	**Original order 2**
Trail Making Task	Trail Making Task	Trail Making Task	Trail Making Task
Backward Digit Span task	Backward Digit Span task	Questionnaire A	Questionnaire A
Questionnaire A	Questionnaire A	Backward Digit Span task	Backward Digit Span task
Spatial Working Memory Task	Spatial Working Memory Task	Questionnaire B	Questionnaire B
Questionnaire B	Questionnaire B	Spatial Working Memory Task	Spatial Working Memory Task
Speech in Noise task	Cattell's Culture Fair test	Questionnaire C	Questionnaire C
Questionnaire C	Questionnaire C	Cattell's Culture Fair test	Speech in Noise task
Cattell's Culture Fair test	Enumeration task	Questionnaire D	Questionnaire D
Questionnaire D	Questionnaire D	Enumeration task	Cattell's Culture Fair test
Enumeration task	Speech in Noise task	Questionnaire E	Questionnaire E
Questionnaire E	Questionnaire E	Speech in Noise task	Enumeration task
Corsi span task	Corsi span task	Corsi span task	Corsi span task
Mental rotation task	Mental rotation task	Mental rotation task	Mental rotation task
AX-Continuous Performance Task	AX-Continuous Performance Task	AX-Continuous Performance Task	AX-Continuous Performance Task

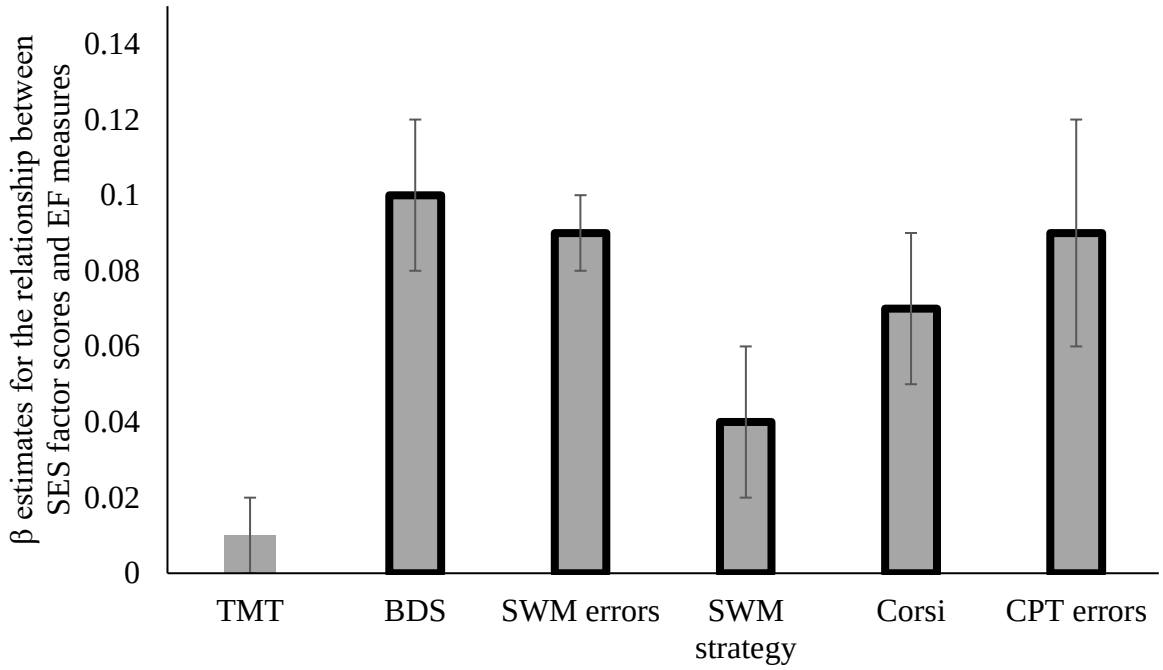
Chapter 3 Appendices

Appendix A

Bar graphs showing the beta coefficients for the cross-sectional analyses reported in **Chapter 3** – sections **3.3.3 - 3.3.5** repeated in the full sample of state school pupils with data at T1.






β estimates for the relationship between SES factor scores and EF measures
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
TMT
BDS
SWM errors
SWM strategy
Corsi
CPT errors

Appendix B

Pearson correlations between the dummy control variables included in the analyses in **Chapter 3** and socioeconomic status indices.

	T2 parental education	Parent highest occupation	Area level deprivation	Free School Meals	SES factor
White	.01	.06**	-.36***	-.12***	.18***
Black	.12***	.03	.16***	.05*	.00
Asian	-.15***	-.15***	.23***	.07**	-.22***
Mixed	.07**	.09***	.01	.03	.06**
Mono-lingual English	.05*	.20***	-.20***	-.02	.20***
Bilingual English	-.07**	-.09***	.14***	.04*	-.13***
English not first language	.02	-.15***	.10***	-.02	-.10***

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

Appendix C

Pearson correlations between the dummy control variables and executive function measures in **Chapter 3**.

	T1 TMT switch	T1 BDS span	T1 SWM errors	T1 SWM strategy	T1 Corsi span	T1 CPT errors	T1 EF factor	T2 TMT switch	T2 BDS span	T2 SWM Errors	T2 SWM strategy	T2 Corsi span	T2 CPT errors	T2 EF factor
White	-.09***	-.05*	-.03	-.01	-.02	-.07	.00	-.06**	-.06**	-.05*	-.01	.01	.04	.00
Black	.03	-.08***	.11***	.09***	-.16***	.03	-.15***	.03	-.11***	.10***	.01	-.19***	-.01	-.14***
Asian	.05**	.10***	-.06**	-.06**	.12***	.07	.11***	.03	.13***	-.03	-.01	.14***	-.04	.11***
Mixed	.02	.03	.00	-.02	.03	-.03	.03	.02	.02	-.01	.02	-.03	.03	.02
Mono-lingual English	.01	-.01	-.05**	-.01	-.04	-.05	.01	.01	-.02	-.02	.00	-.06	-.01	-.01
Bilingual English	.04*	.06**	-.02	-.01	.05*	.01	.05**	.05*	.07***	-.03	-.05*	.07*	.03	.06**
English not first language	-.05**	-.06**	.09***	.01	-.01	.05	-.07***	-.06**	-.05**	.06**	.05*	-.02	-.02	-.05**

Note. TMT = Trail Making Task; BDS = Backwards Digit Span; SWM = Spatial Working Memory; CPT = Continuous Performance Task. * $p < .05$, ** $p < .01$, *** $p < .001$.

Appendix D

Estimates for the effects of socioeconomic status on different executive function measures from Chapter 3 model 2 with the addition of auxiliary variables.

Predictor	Cross-sectional		Longitudinal	
	Standardised β [CIs]	Raw β [CIs]	Standardised β (CIs)	Raw β (CIs)
Parental education	.05 [.00, .09]*	0.04 [0.00, 0.08]	.01 [-.03, .05]	0.00 [-0.03, 0.04]
Highest occupation	.05 [.00, .09]*	0.02 [0.01, 0.03]	.05 [.01, .08]*	0.02 [0.00, 0.03]
Area level deprivation	-.01 [-.05, .03]	-0.01 [-0.03, 0.02]	.00 [-.04, .03]	0.00 [-0.02, 0.02]
Free School Meals	-.04 [-.08, .00]*	-0.07 [-0.14, 0.00]	-.04 [-.08, -.01]*	-0.08 [-0.14, -0.02]
Full model R^2	.05		.31	

Appendix E

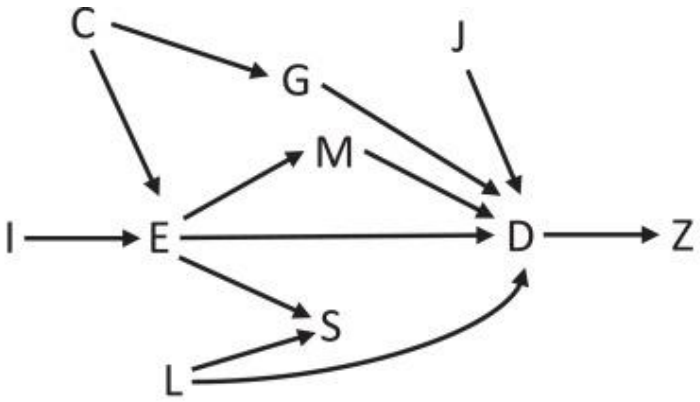
Estimates for the effects of socioeconomic status on different executive function measures from Chapter 3 model 3 with the addition of auxiliary variables.

	Cross-sectional models			Longitudinal models		
	Standardised β [CIs]	Raw β [CIs]	R^2	Standardised β [CIs]	Raw β [CIs]	R^2
TMT switch	-.01 [-.05, .03]	-0.01 [-0.04, 0.02]	.01	.00 [-.04, .04]	0.00 [-0.03, 0.03]	.05
BDS span	.06 [.02, .10]**	0.07 [0.02, 0.11]	.03	.06 [.03, .10]***	0.08 [0.04, 0.12]	.26
SWM errors	-.05 [-.09, -.01]*	-0.83 [-1.50, -0.17]	.03	-.03 [-.07, .01]	-0.44 [-1.08, 0.20]	.12
SWM strategy	-.03 [-.09, -.01]	-0.10 [-0.54, 0.05]	.01	.00 [-.04, .04]	-0.02 [-0.17, 0.14]	.04
Corsi span	.05 [.00, .10]	0.05 [0.00, 0.09]	.04	.07 [.01, .13]*	0.08 [0.01, 0.15]	.25
CPT errors	-.09 [-.17, -.01]*	-0.60 [-1.14, -0.06]	.02	-.02 [-.12, .08]	-0.16 [-0.83, 0.50]	.20

Chapter 4 Appendices

Appendix A

Directed acyclic graph tutorial from Digitale et al. (2022).



To identify the causal effect of E on D, we must block all non-causal paths and none of the causal paths between the two variables.

Causal paths linking E and D:
E → M → D
E → D

Non-causal paths linking E and D and how to block them:
E ← C → G → D (block by controlling for C or G)
E → S ← L → D (blocked provided we do not control for S)

Key terms:

- C confounds the association of E and D.
- G can be controlled to block the confounding path between E and D.
- M partially mediates the effect of E on D.
- S is a collider on a non-causal path between E and L, and therefore a collider on a non-causal path between E and D. Controlling or restricting on S will create a biased association between E and D.
- Z is a descendant of D.
- I is an instrumental variable, such as randomization, for the effect of E on D.
- J causes D and will therefore be an effect modifier of any other cause of D on at least one scale (additive or multiplicative).

Key concepts:

- Paths are sequences of arrows, of any direction, connecting two variables and may be causal or non-causal.
- Paths are causal if each variable causes the subsequent variable (all the arrows point in the same direction).
- Paths are non-causal if the arrows do not all point in the same direction. They contain confounders and/or colliders.
- Confounding occurs because of common (shared) causes (e.g., C) of E and D. To estimate the effect of E on D, it is necessary to control for such common causes or other variables along the non-causal path. Control for either C or G would be adequate to eliminate the confounding due to C. G may be preferable, for example, if it is easier to obtain a high-quality measurement of G.
- Mediators (e.g., M) are caused by E and, in turn, cause D. They should not be controlled for to estimate the total effect of E on D.
- Colliders (e.g., S) are so named because they have two arrows pointing into them. Colliders on a path block that path unless they are conditioned on (e.g., by controlling for them) or a consequence of the collider is conditioned on.
- Analyses should not adjust for, stratify on, or in any way condition on descendants of D (e.g., Z).
- Instrumental variables (e.g., I) are variables related to the exposure of interest that have no association with the outcome except through the exposure. Instrumental variables analysis (a technique common in the economics literature) can be used to derive effect estimates when there is intractable confounding of E and D.
- Effect modifiers (e.g., J) are variables that cause D and modify the effect of other causes of D, such as E. If E and J both cause D, then J modifies the effect of E on D on at least one effect-measure scale (additive or multiplicative).

Appendix B

Model 1 parameter estimates with the addition of ethnicity and first language controls.

	Std. r [95% CIs]	**Raw r [95% CIs]**
Socioeconomic status.f <-> Black ethnicity	-.15 [-.21, -.09]***	-0.06 [-0.08, -0.04]
Socioeconomic status.f <-> Asian ethnicity	-.36 [-.41, -.30]***	-0.17 [-0.20, -0.14]
Socioeconomic status.f <-> Bilingual	-.18 [-.23, -.12]***	-0.08 [-0.10, -0.05]
Socioeconomic status.f <-> English not first language	-.14 [-.20, -.09]***	-0.06 [-0.08, -0.04]
	Std. β [95% CIs]	**Raw β [95% CIs]**
Socioeconomic status.f -> GCSE.f	.26 [.20, .31]***	0.46 [0.35, 0.57]
Age 11 attainment.f -> GCSE.f	.71 [.68, .74]***	1.28 [1.18, 1.37]
Black ethnicity -> GCSE.f	.02 [-.02, .05]	0.08 [-0.07, 0.23]
Asian ethnicity -> GCSE.f	.18 [.14, .21]***	0.67 [0.51, 0.83]
Bilingual -> GCSE.f	.09 [.06, .12]***	0.38 [0.52, 0.21]
English not first language -> GCSE.f	.15 [.12, .18]***	0.65 [0.50, 0.79]

Appendix C

Parameter estimates, CIs and *p*-values for the key paths in model 1 after auxiliary variables were added.

	Std. β [95% CI]	**Raw β [95% CI]**	***p*-value**
Socioeconomic status -> GCSEs	.06 [-.01, .12]	0.11 [-0.02, 0.23]	.085
Age 11 attainment -> GCSEs	.78 [.75, .81]	1.49 [1.35, 1.62]	< .001
Δ working memory -> GCSEs	.28 [.20, .35]	5.11 [3.08, 7.14]	< .001
Socioeconomic status -> Δ working memory	.11 [-.01, .24]	0.01 [0.00, 0.03]	.080

Appendix D

Parameter estimates, CIs and *p*-values for the key paths in model 2 after auxiliary variables were added.

	Std. β [95% CIs]	Raw β [95% CIs]
Socioeconomic status factor -> T2 BDS span	.09 [.04, .14]***	0.08 [0.04, 0.13]
Socioeconomic status factor -> T2 Corsi span	.10 [.02, .18]*	0.09 [0.02, 0.16]
Socioeconomic status factor -> T2 SWM errors	-.06 [-.12, -.01]*	-0.70 [-1.45, -0.08]
T1 BDS span -> T2 BDS span	.48 [.45, .51]***	0.53 [0.49, 0.56]
T1 Corsi span -> T2 Corsi span	.46 [.41, .52]***	0.54 [0.48, 0.62]
T1 SWM errors -> T2 SWM errors	.31 [.27, .35]***	0.29 [0.26, 0.33]

	GCSE English		GCSE Maths		GCSE Science	
	Std. β [95% CIs]	Raw β [95% CIs]	Std. β [95% CIs]	Raw β [95% CIs]	Std. β [95% CIs]	Raw β [95% CIs]
Reading 11y	.14 [.09, .18]***	0.31 [0.21, .41]	-.02 [-.06, .02]	-0.06 [-0.16, .05]	.06 [.02, .10]**	0.15 [0.04, .26]
Writing 11y	.25 [.21, .30]***	0.60 [0.49, .71]	.02 [-.02, .06]	0.05 [-0.07, .16]	.05 [.00, .09]*	0.13 [0.01, .25]
Maths 11y	.15 [.10, .19]***	0.29 [0.20, .38]	.56 [.53, .60]***	1.27 [1.18, 1.36]	.40 [.36, .45]***	0.91 [0.81, 1.01]
Science 11y	.14 [.09, .19]***	0.36 [0.24, .47]	.17 [.13, .21]***	0.48 [0.36, .60]	.18 [.14, .23]***	0.52 [0.39, .65]
Socioeconomic status.f	.11 [.07, .16]***	0.19 [0.12, 0.27]	.09 [.05, .13]***	0.18 [0.10, 0.26]	.12 [.07, .16]***	0.22 [0.14, 0.31]
T2 BDS span	.12 [.09, .16]***	0.22 [0.16, 0.29]	.13 [.09, .16]***	0.26 [0.19, 0.32]	.13 [.10, .17]***	0.27 [0.20, 0.34]
T2 Corsi span	.08 [.03, .13]**	0.16 [0.06, 0.26]	.15 [.11, .20]***	0.33 [0.24, 0.43]	.12 [.07, .16]***	0.23 [0.15, 0.35]
T2 SWM errors	-.05 [-.08, -.01]*	-0.01 [-0.01, 0.00]	-.07 [-.10, -.03]***	-0.01 [-0.02, -0.01]	-.06 [-.10, -.03]***	-0.01 [-0.02, 0.00]

Appendix E

Covariance matrices for the standardised correlations between **a.** age 11 attainment measures and **b.** T1 working memory measures in models 2 and 3.

a

	1	2	3
1. BDS span			
2. Corsi span	.34***		
3. SWM errors	-.28***	-.29***	

b

	1	2	3	4
4. Reading				
5. Writing	.66***			
6. Maths	.61***	.60***		
7. Science	.62***	.66***	.64***	

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

Appendix F

Standardised and unstandardised coefficients and CIs for the associations of age 11 attainment measures, socioeconomic status indices, T2 working memory measures, ethnicity and first language status with attainment at age 16 in English, maths and science.

	GCSE English		GCSE Maths		GCSE Science	
	Std. β [95% CIs]	**Raw β [95% CIs]**	**Std. β [95% CIs]**	**Raw β [95% CIs]**	**Std. β [95% CIs]**	**Raw β [95% CIs]**
Reading 11y	.15 [.10, .19]***	0.33 [0.23, 0.43]	-.01 [-.05, .03]	-0.03 [-0.12, 0.07]	.08 [.04, .12]***	0.20 [0.09, 0.30]
Writing 11y	.26 [.21, .30]***	0.61 [0.50, 0.72]	.03 [-.01, .07]	0.07 [-0.04, 0.18]	.06 [.01, 10]*	0.15 [0.03, 0.27]
Maths 11y	.13 [.09, .18]***	0.26 [0.17, 0.35]	.55 [.51, .59]***	1.23 [1.14, 1.32]	.38 [.34, .43]***	0.86 [0.77, 0.96]
Science 11y	.14 [.09, .18]***	0.34 [0.23, 0.46]	.16 [.12, .20]***	0.46 [0.34, 0.58]	.18 [.14, .22]***	0.51 [0.39, 0.64]
Parent education	.07 [.03, .10]**	0.13 [0.05, 0.20]	.07 [.03, .10]***	0.14 [0.07, 0.22]	.07 [.03, .10]***	0.15 [0.06, 0.23]
Highest occupation	.07 [.03, .10]***	0.06 [0.03, 0.09]	.05 [.01, .08]**	0.05 [0.01, 0.08]	.08 [.04, .11]***	0.07 [0.04, 0.11]
Household income	-.07 [-.10, -.04]***	-0.29 [-0.43, -0.16]	-.09 [-.11, -.06]***	-0.42 [-0.55, -0.28]	-.08 [-.11, -.05]***	-0.39 [-0.54, -0.25]
Area deprivation	-.05 [-.09, -.02]**	-0.07 [-0.11, -0.02]	-.05 [-.08, -.02]**	-0.07 [-0.12, -0.02]	-.05 [-.09, -.02]**	-0.08 [-0.13, -0.03]
T2 BDS span	.12 [.08, .16]***	0.21 [0.15, 0.27]	.12 [.08, .15]***	0.23 [0.17, 0.30]	.12 [.09, .16]***	0.25 [0.18, 0.32]
T2 Corsi span	.07 [.02, .12]**	0.13 [0.03, 0.22]	.14 [.09, .18]***	0.30 [0.20, 0.39]	.10 [.06, .15]***	0.23 [0.13, 0.33]
T2 SWM errors	-.06 [-.09, -.02]**	-0.01 [-0.01, 0.00]	-.08 [-.11, -.04]***	-0.01 [-0.02, -0.01]	-.08 [-.11, -.04]***	-0.01 [-0.02, -0.01]
Black ethnicity	.01 [-.02, .05]	0.06 [-0.09, 0.21]	-.01 [-.04, .02]	-0.06 [-0.21, 0.09]	.02 [-.01, .05]	0.10 [-0.06, 0.26]
Asian ethnicity	.09 [.06, .13]***	0.33 [0.20, 0.46]	.10 [.06, .13]***	0.39 [0.26, 0.52]	.11 [.07, .14]***	0.43 [0.29, 0.57]
Bilingual from birth	.01 [-.02, .05]	0.05 [-0.08, 0.18]	.05 [.02, .08]**	0.22 [0.10, 0.35]	.05 [.02, .08]**	0.23 [0.09, 0.37]
English not first language	.06 [.03, .09]***	0.25 [0.11, 0.39]	.08 [.05, .11]***	0.39 [0.26, 0.53]	.12 [.08, .15]***	0.54 [0.40, 0.69]

Note. * p < .05, ** p < .01, *** p < .001. .f signifies factor

Standardised and unstandardised coefficients and CIs for the associations of age 11 attainment measures, the socioeconomic status factor, and T2 working memory measures with attainment at age 16 in English, maths, and science

	Std. r [95% CIs]	**Raw r [95% CIs]**
Parent education <-> Black ethnicity	.09 [.04, .13]**	0.03 [0.01, 0.05]
Parent education <-> Asian ethnicity	-.10 [-.15, -.05]***	-0.04 [-0.06, -0.02]
Parent education <-> Bilingual	-.05 [-.09, .00]	-0.02 [-0.02, 0.00]
Parent education <-> English not first language	.01 [-.04, .05]	0.00 [-0.01, 0.02]
Parent occupation <-> Black ethnicity	.00 [-.04, .04]	0.00 [-0.03, 0.03]
Parent occupation <-> Asian ethnicity	-.11 [-.16, -.07]***	-0.10 [-0.14, -0.06]
Parent occupation <-> Bilingual	-.11 [-.16, -.07]***	-0.10 [-0.13, -0.06]
Parent occupation <-> English not first language	-.18 [-.22, -.13]***	-0.14 [-0.17, -0.10]
Free School Meals <-> Black ethnicity	.07 [.03, .11]**	0.01 [0.01, 0.02]
Free School Meals <-> Asian ethnicity	.09 [.04, .13]***	0.02 [0.01, 0.02]
Free School Meals <-> Bilingual	.02 [-.02, .06]	0.00 [0.00, 0.01]
Free School Meals <-> English not first language	-.02 [-.06, .02]	0.00 [-0.01, 0.00]
Area deprivation <-> Black ethnicity	.25 [.21, .28]***	0.12 [0.10, 0.14]
Area deprivation <-> Asian ethnicity	.27 [.23, .30]***	0.16 [0.13, 0.18]
Area deprivation <-> Bilingual	.11 [.07, .15]***	0.06 [0.04, 0.08]
Area deprivation <-> English not first language	.12 [.08, .16]***	0.06 [0.04, 0.08]
	Std. β [95% CIs]	**Raw β [95% CIs]**
Parent education -> T2 BDS span	.02 [-.03, .06]	0.02 [-0.03, 0.06]
Parent education -> T2 Corsi span	-.01 [-.08, .06]	-0.01 [-0.08, 0.06]
Parent education -> T2 SWM errors	.03 [-.01, .08]	0.47 [-0.20, 1.15]
Parent occupation -> T2 BDS span	.04 [.00, .08]	0.02 [0.00, 0.04]
Parent occupation -> T2 Corsi span	.08 [.02, .14]*	0.04 [0.01, 0.06]
Parent occupation -> T2 SWM errors	-.04 [-.08, .01]	-0.25 [-0.53, 0.04]
Free School Meals -> T2 BDS span	-.06 [-.09, -.02]**	-0.14 [-0.22, -0.05]
Free School Meals -> T2 Corsi span	-.02 [-.08, .03]	-0.05 [-0.17, 0.07]
Free School Meals -> T2 SWM errors	.05 [.01, .09]*	1.50 [0.23, 2.75]
Area deprivation -> T2 BDS span	-.01 [-.04, .03]	0.00 [-0.03, 0.02]
Area deprivation -> T2 Corsi span	-.02 [-.09, .04]	-0.02 [-0.06, 0.03]
Area deprivation -> T2 SWM errors	.03 [-.01, .07]	0.31 [-0.10, 0.72]
T1 BDS span -> T2 BDS span	.47 [.45, .51]***	0.53 [0.49, 0.56]
T1 Corsi span -> T2 Corsi span	.47 [.41, .52]***	0.54 [0.47, 0.61]
T1 SWM errors -> T2 SWM errors	.31 [.27, .34]***	0.29 [0.26, 0.33]

Appendix G

Parameter estimates, CIs and *p*-values for the key paths in model 3 after auxiliary variables were added.

	GCSE English		**GCSE Maths**		**GCSE Science**	
	Std. β [95% CIs]	**Raw β [95% CIs]**	**Std. β [95% CIs]**	**Raw β [95% CIs]**	**Std. β [95% CIs]**	**Raw β [95% CIs]**
Reading 11y	.14 [.09, .18]***	0.30 [0.20, 0.40]	-.03 [-.07, .01]	-0.06 [-0.16, 0.04]	.06 [.01, .10]**	0.14 [0.04, 0.25]
Writing 11y	.25 [.21, .30]***	0.59 [0.48, 0.70]	.02 [-.03, .06]	0.04 [-0.07, 0.15]	.05 [.00, .09]*	0.12 [0.00, 0.24]
Maths 11y	.15 [.10, .19]***	0.29 [0.20, 0.38]	.57 [.53, .60]***	1.27 [1.18, 1.36]	.40 [.36, .45]***	0.90 [0.81, 1.00]
Science 11y	.14 [.09, .18]***	0.34 [0.22, 0.46]	.16 [.12, .20]***	0.47 [0.35, 0.58]	.18 [.13, .22]***	0.51 [0.38, 0.63]
Parent education	.06 [.02, .10]**	0.12 [0.05, 0.19]	.06 [.03, .10]**	0.13 [0.06, 0.21]	.07 [.03, .11]***	0.15 [0.07, 0.23]
Parent occupation	.05 [.02, .09]**	0.05 [0.01, 0.08]	.03 [-.01, .06]	0.03 [-0.01, 0.06]	.05 [.02, .09]**	0.05 [0.02, 0.09]
Free School Meals	-.07 [-.10, -.04]***	-0.30 [-0.43, -0.16]	-.09 [-.12, -.06]***	-0.43 [-0.56, -0.29]	-.08 [-.11, -.05]***	-0.41 [-0.56, -0.26]
Area deprivation	-.02 [-.06, .01]	-0.03 [-0.08, 0.01]	-.02 [-.05, .01]	-0.03 [-0.70, 0.02]	-.01 [-.04, .02]	-0.02 [-0.07, 0.03]
T2 BDS span	.13 [.09, .16]***	0.22 [0.16, 0.29]	.13 [.10, .16]***	0.26 [0.19, 0.32]	.14 [.10, .17]***	0.27 [0.20, 0.34]
T2 Corsi span	.08 [.03, .13]**	0.16 [0.06, 0.25]	.15 [.11, .20]***	0.33 [0.25, 0.44]	.12 [.07, .17]***	0.25 [0.15, 0.36]
T2 SWM errors	-.05 [-.09, -.01]**	-0.01 [-0.01, 0.00]	-.07 [-.10, -.04]***	-0.01 [-0.02, -0.01]	-.07 [-.10, -.03]***	-0.01 [-0.02, -0.01]

	Std. β [95% CIs]	Raw β [95% CIs]
Parent education -> T2 BDS span	.02 [-.03, .06]	0.02 [-0.03, 0.07]
Parent education -> T2 Corsi span	-.01 [-.07, .06]	-0.01 [-0.07, 0.07]
Parent education -> T2 SWM errors	.03 [-.02, .07]	0.37 [-0.30, 1.05]
Parent occupation -> T2 BDS span	.04 [.00, .08]*	0.02 [0.00, 0.04]
Parent occupation -> T2 Corsi span	.08 [.01, .14]*	0.04 [0.01, 0.06]
Parent occupation -> T2 SWM errors	-.04 [-.08, .01]	-0.23 [-0.52, 0.05]
Free School Meals -> T2 BDS span	-.06 [-.09, -.02]**	-0.14 [-0.23, -0.05]
Free School Meals -> T2 Corsi span	-.02 [-.07, .04]	-0.04 [-0.16, 0.08]
Free School Meals -> T2 SWM errors	.05 [.01, .09]*	1.51 [0.23, 2.79]
Area deprivation -> T2 BDS span	.00 [-.04, .03]	0.00 [-0.03, 0.03]
Area deprivation -> T2 Corsi span	-.02 [-.08, .05]	-0.01 [-0.06, 0.03]
Area deprivation -> T2 SWM errors	.03 [-.01, .07]	0.32 [-0.09, 0.73]
T1 BDS span -> T2 BDS span	.48 [.45, .51]***	0.53 [0.49, 0.56]
T1 Corsi span -> T2 Corsi span	.47 [.42, .52]***	0.55 [0.48, 0.62]
T1 SWM errors -> T2 SWM errors	.31 [.27, .35]***	0.29 [0.26, 0.33]