[under review]

Nature, nurture and nonshared environment in cognitive development

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Abstract

One of the most important findings from behavioural genetic research is that nature, not nurture, makes children in a family similar in personality and psychopathology. The same research provides the strongest available evidence for the importance of environmental influence controlling for genetics, but it shows that environmental influences are not due to nurture; they are not shared by family members. Cognitive traits such as cognitive abilities and educational achievement are thought to be an exception, with half of the environmental variance attributed to shared environmental influences. However, most of this cognitive research has involved children. A developmental perspective indicates that shared environmental influence on cognitive abilities and educational achievement declines from accounting for 20-30% of the variance in childhood to 10-20% in adolescence and to 0% by early adulthood. Educational attainment (years of schooling) is the exception with lasting shared environmental influence (30%) driven by decisions made in adolescence to go to university, which shows the greatest shared environmental influence (47%). We conclude that environmental influences on individual differences in cognitive development are, in the long run, nonshared. We discuss the far-reaching scientific and societal implications of these findings for understanding the nonshared environmental causes of individual differences in cognitive abilities in adulthood.

Introduction

Twin and adoption studies have shown that inherited DNA differences account for about half of the variance in behavioural traits [1,2]. The other half of the variance led to a finding with at least as far-reaching implications. Because family members share both genes and environment, the rationale for twin and adoption research was to disentangle the effects of nature and nurture in family resemblance. Environmentalism, which dominated the behavioural sciences for most of the twentieth century [3], assumed that behavioural traits run in families for environmental reasons, ignoring the fact that first-degree relatives are fifty percent similar genetically. To the contrary, genetic research has shown that familial resemblance for personality and psychopathology can be explained entirely by genetic similarity between relatives. The environment is important, accounting for the other half of the variance, but it is not nurture in the sense of shared family environment. The salient environmental influences are not shared by children growing up in the same family.

The importance of environmental differences within rather than between families was first highlighted in 1976 by Loehlin and Nichols [4] who proposed that environmental effects seem to 'operate almost randomly' (p. 92), although earlier passing references can be found [5,6]. In 1981, this phenomenon was labelled *nonshared environment* [7]. In 1987, a review concluded that nonshared environment is the major source of environmental variance for personality and psychopathology [8], which has become one of the most replicated findings in behavioural genetics [9]. In contrast, general cognitive ability yielded substantial estimates of shared environmental influence, accounting for as much as 30 percent of the variance. However, the 1987 review noted: 'Although it has been thought that cognitive abilities represent an exception to this rule, recent data suggest that environmental variance that affects IQ is also of the nonshared variety *after adolescence*' [8] (p. 1). This review was published with 32 commentaries, which did not disagree with the revolutionary finding that environmental influence was largely nonshared for personality and psychopathology. However, the suggestion that this was also true for cognitive traits after adolescence met with incredulity [10,11].

It is important to know whether environmental influences on cognitive traits are nonshared after adolescence because research trying to identify environmental influences on cognitive traits has assumed that the salient environmental influences are shared by siblings growing up in the same family, such as influences of parents, families, and schools. Associations between such family-wide environmental measures and cognitive traits have been found in childhood independent of genetics [12]. However, if environmental variance after adolescence is nonshared, little is known about the environmental factors responsible for individual differences in cognitive traits in adulthood.

At the outset, the distinction between *what is* and *what could be* warrants emphasis. Genetic research describes genetic and environmental sources of variance as they exist in a particular population at a particular time. The research does not predict what could be in other populations at other times. In other words, parents *can* without doubt affect their children's cognitive development, but the question we address is whether individual differences in parenting *do* have an effect on individual differences in their children's cognitive traits. For the same reason, finding that environmental variance is nonshared does not imply that family or school interventions are futile. Another caveat is that the research we review cannot be safely generalised beyond the samples studied, which means that these studies are limited to the normal range of families who participate in research, which does not include, for example, the extremes of neglect or abuse.

Throughout this review, in order to focus on shared and nonshared environment, we have ignored the major source of individual differences in cognitive traits: genetics, inherited differences in DNA sequence, which accounts for about half of the variance of cognitive traits [1]. We also limit our review to the normal distribution of cognitive traits because much less research is available at the extremes. Also, common disorders are likely to be the quantitative extremes of the same genetic and environmental factors responsible for normal distributions [13].

The present review has three goals. First, we review the extensive research relevant to the hypothesis that shared environmental variance for general cognitive ability diminishes in adolescence and is negligible by young adulthood. However, other cognitive traits -- specific cognitive abilities, educational achievement, and educational attainment -- might have different developmental trajectories, so the second goal is to review shared and nonshared environmental estimates for cognitive traits other than general cognitive ability. Third, we consider the implications of these findings for understanding the environmental causes of cognitive traits.

General cognitive ability

Twin and adoption studies consistently converge on the conclusion that environmental influences on general cognitive ability (‘g’, aka intelligence, IQ) are substantially due to nurture in childhood. However, a developmental perspective shows that these shared environmental influences decline in adolescence and disappear in adulthood. By adulthood, all environmental influences on general cognitive ability are nonshared. In this section, we summarise the results of our review, with more details provided in Supplementary Information 1.

Panel A of Figure 1 summarises twin study estimates of shared environmental influence by age, as extracted from a 2015 meta-analysis of twin correlations across hundreds of 'higher-level cognitive functions' for more than 200,00 twin pairs [2]. Estimates of shared environment were 32% for children (below age 12), 8% for adolescents (12-17 years), and 0% in adulthood (18-64 and 65+). As shown in Panel B, a mega-analysis of 11,000 twin pairs in six recent twin studies with standard measures of g demonstrated a significant decrease in shared environmental influence from 33% in childhood (average age 9 years) to adolescence (18% at 12 years; 16% at 17 years). A recent extension of the largest of these twin studies to age 25 showed a further decline to 8% [14].

The most direct test of the hypothesis that family resemblance is caused by shared environment is the correlation between adoptive relatives, genetically unrelated family members who live together. Adoption studies before the 1980s yielded an average g correlation of 0.24 between adoptive parents and their adopted children [15]. However, two more recent adoption studies found correlations near zero in childhood and adolescence, casting doubt on the conclusion that parents' g-related traits are transmitted environmentally to their children [16,17].

Importantly, parents' g does not capture all the shared environmental influences relevant to their children's cognitive development. Resemblance between adoptive siblings, genetically unrelated children reared in the same adoptive family, directly estimates the importance of all shared environmental influences that affect siblings growing up together in the same family. Studies of adoptive siblings before the 1980s yielded a g correlation of 0.32, indicating that a third of the total variance of g could be attributed to shared environmental influence [15].

However, no one noticed that this correlation was based on pre-adolescent children. The first study of post-adolescent adoptive siblings (average age 18 years) reported a correlation of -0.03 [18], a finding confirmed in two additional studies of post-adolescent adoptive siblings, which yielded an average g correlation of -0.01, in contrast to a correlation of 0.25 from 11 recent studies of pre-adolescent adoptive siblings [19]. The strongest evidence for the decline of shared environmental influence comes from a more recent longitudinal study of adoptive siblings from childhood to adolescence [20]. The correlation at the average age of 8 was 0.33 but dropped to 0.02 when the same children were tested again 10 years later. These findings are also supported by a meta-analysis of longitudinal data through adolescence from recent adoption and twin studies [21].

Dramatic confirmation of the hypothesis that shared environmental influence on g is negligible in adulthood comes from adult identical twins who had been reared apart: they are as similar as adult identical twins who had been reared together [19]. In other words, identical twins growing up in the same family are no more similar for g than identical twins growing up in different families.

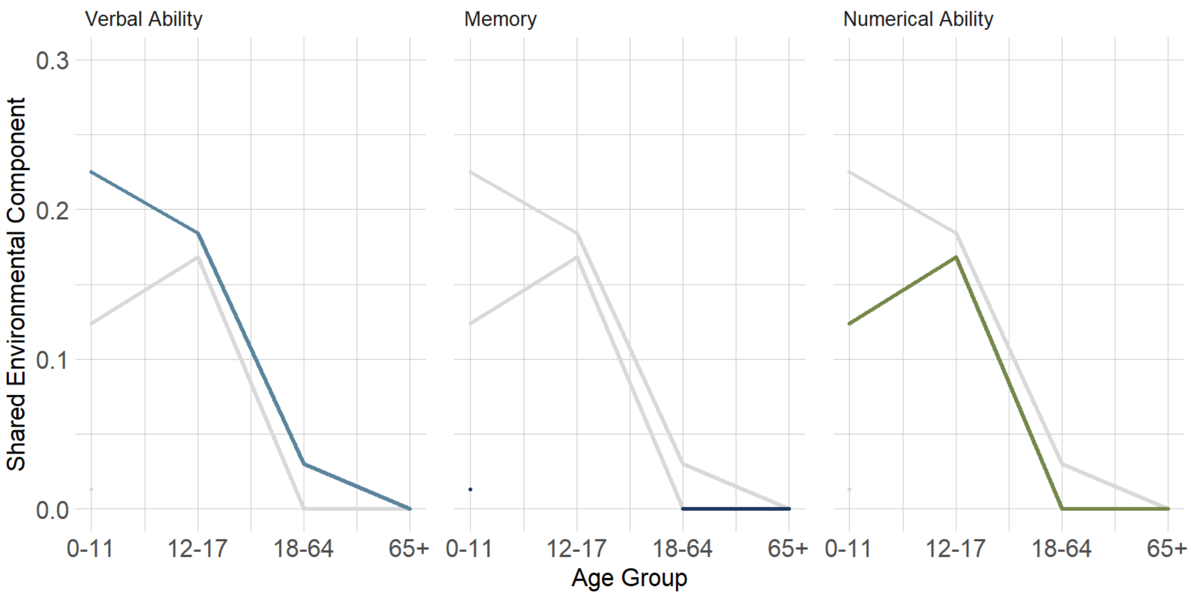
In summary, although general cognitive ability has been thought to be an exception to the rule that environmental influence is nonshared, it is now clear that shared environmental influence on g has negligible long-term impact after children leave home and make their own way in the world. In other words, environmental influences that account for almost half the variance of general cognitive ability are, in the long run, not caused by nurture in the sense of systematic environmental effects of parenting or schools shared by siblings growing up together. The salient environmental influences responsible for individual differences in general cognitive ability in adulthood are nonshared, making siblings who grew up in the same family as different as children reared in different families.

Specific cognitive abilities

Does this developmental pattern of results for g extend to specific cognitive abilities including verbal traits like vocabulary and verbal fluency and nonverbal traits like memory and spatial ability? Previous reviews of the genetics of specific cognitive traits were limited to twin research and are more than 30 years old [22,23,24]. Most of the twin studies available at that time involved samples too small to provide reliable estimates of shared environmental influence and they did not consider age. In this section, we review newer twin and adoption studies from a developmental perspective, with more details provided in Supplementary Information 2.

Estimates of shared environmental influence derived from two recent reviews of twin studies indicate that, like g, specific cognitive abilities show substantial shared environmental influence in childhood that disappears in adulthood [2,25]. As shown in Figure 2, estimates for broad categories of verbal and numerical ability extracted from a 2015 meta-analysis [2] were about 20% in childhood and adolescence and declined to zero in adulthood. Memory ability was only assessed in adulthood and showed no shared environmental influence.

Figure 2. Twin study estimates of shared environmental influence declines from childhood to adulthood in twin studies of broad categories of verbal, memory and numerical ability extracted from a 2015 meta-analysis [2].



Twin correlations extracted from a more refined 2022 meta-analysis of adequately powered twin studies of 11 specific cognitive abilities [25] also found a general downward developmental trend, with all abilities yielding estimates less than 10% in adulthood. (See

Figure 3.) On average across the 11 abilities, estimates of shared environment were 40% in early childhood, 13% in middle childhood, 12% in adolescence, 3% in adulthood, and 1% in older adulthood.

Figure 3. Shared environmental influence declines from childhood to adulthood in our analyses of twin correlations for 11 cognitive abilities extracted from a 2022 meta-analysis [25].

Much less research is available for specific cognitive traits using the adoption design. The database for adoptive siblings is too weak to test the hypothesis of declining influence of experiences shared by siblings. The average weighted correlation between adoptive parents and their adopted children was 0.03 across childhood and adolescence in three adoption studies [17,20,18], indicating little shared environmental transmission from parents to offspring.

In summary, although more adoption research is needed, twin studies of specific cognitive abilities, like g, reveal substantial shared environmental influence in childhood that fades by early adulthood.

Educational achievement

Educational achievement is meant to assess what is taught at school, in contrast to cognitive abilities which connote inherent intellectual capabilities. Although g and school achievement are strongly correlated (~0.70), non-cognitive traits such as conscientiousness contribute independently towards achievement [26].

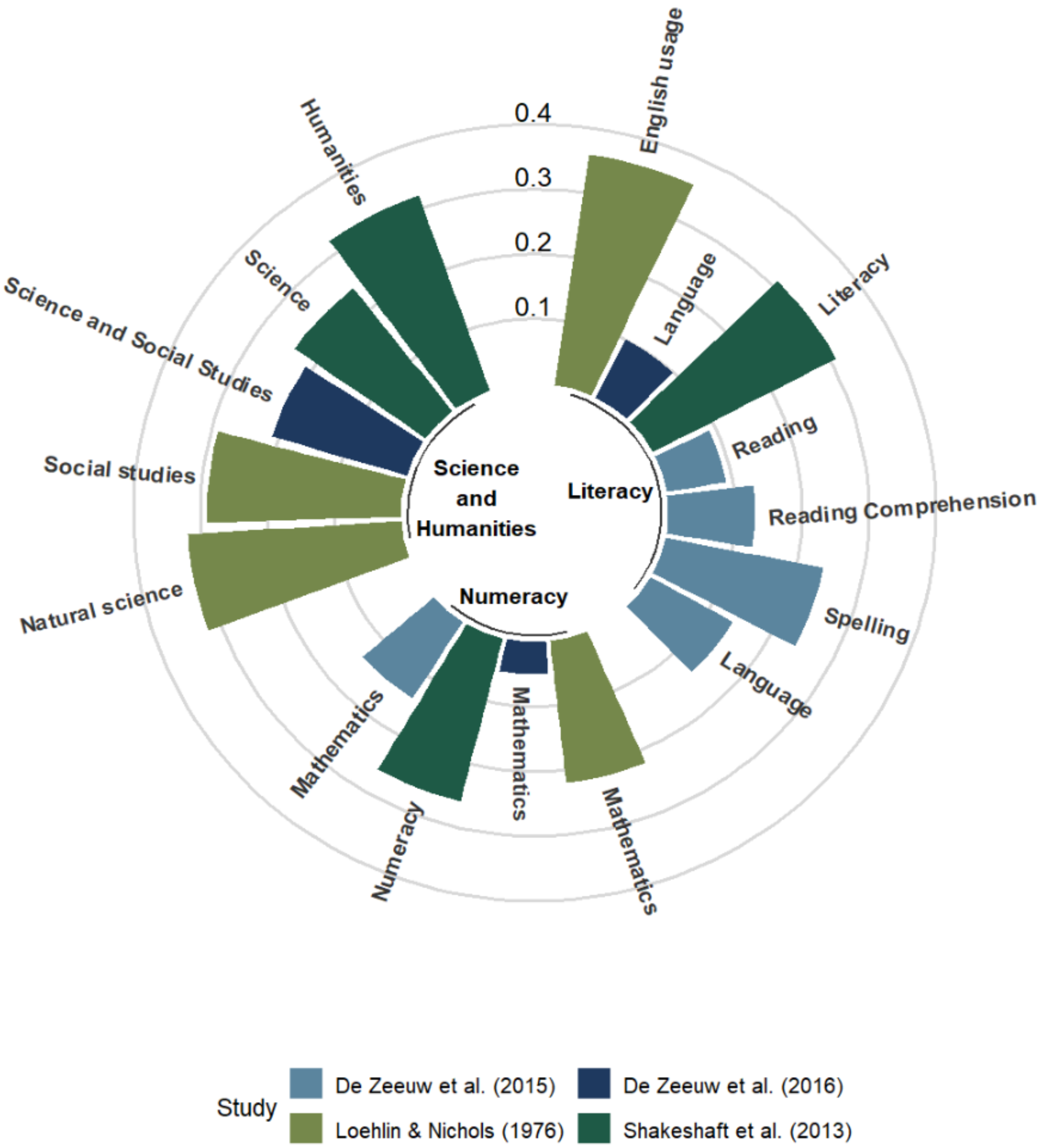
Using national test results for literacy, numeracy and science, large twin studies in the US at age 13 [4] and in the UK at age 16 [27] found shared environmental estimates of about 30%. However, a large Dutch study yielded an estimate of only 8% for a total score on a national test administered at age 12 [28], although an earlier Dutch analysis using the same test at the same age yielded an estimate of 27% [29]. (Supplementary Information 3 includes more detail about studies in this section.)

A meta-analysis of 28 reports with diverse measures from 11 twin studies found an average shared environmental estimate of only about 12% [30]. The review was limited to primary school and most of the samples were in the first three years of school, but this does not seem to be the sole reason for the lower estimate because the only longitudinal twin analysis found estimates of about 20% that did not vary systematically across the school years [31].

The most compelling evidence for the importance of shared environment for educational achievement is a correlation of 0.24 for adoptive siblings for scores on a national examination at the end of primary school in Denmark [32].

Figure 4 shows that the estimates of shared environmental influence did not differ much across subjects within the three larger twin studies [4,28,27] and the meta-analysis [30]. Nor did the results vary systematically from the early school years to secondary school (Supplementary Information 3). Although these estimates vary widely across studies, the average shared environment estimate from Figure 4 is 21%.

Figure 4. Circular bar chart of shared environmental estimates for educational achievement across subjects (grouped by literacy, numeracy and science) assessed using nation-wide tests in three large twin studies [4,28,31] and in a meta-analysis of multiple reports from 11 studies [30].



Does shared environmental influence on educational achievement fade after secondary school, as it does for cognitive abilities? Two UK reports suggest that it does. In the UK, compulsory secondary schooling ends at age 16. A gatekeeper for enrolling at university is a two-year university preparatory course called Advanced Level (A-level). A twin analysis of A-level examination scores yielded shared environment estimates of only 2% for STEM subjects and 11% for humanities [33]. Even more surprisingly, university grades showed no significant shared environmental influence [34].

Although these results are based on single studies of A-level scores and university grades, the evidence as it stands suggests that educational achievement, like cognitive abilities, shows substantial shared environmental influence in primary and secondary education (about 20%) that fades during tertiary education.

Educational attainment

If shared environmental influence on educational achievement disappears in adulthood, one might suppose that educational attainment -- years of schooling, which can only be assessed in adulthood after schooling has been completed -- would also show no shared environmental influence. But this is not the case. Because educational attainment can be assessed with a single item and is used as a demographic index in research, large samples of twins are available. In a mega-analysis of educational attainment from 28 twin cohorts with 81,894 twin pairs, shared environmental influence was estimated as 31% [35]. An earlier meta-analysis yielded an estimate of 36% [36].

The only adequately powered study of educational attainment using the adoptive sibling design strongly supports these twin results, reporting a correlation of 0.37 for adoptive siblings [37]. In contrast, across eight adoption studies, the average weighted correlation for educational attainment of adoptive parents and their adopted children is 0.08, indicating that parents' educational attainment has little shared environmental effect on their children. (See Supplementary Information 4 for details and for a discussion of the effects of assortative mating, which is substantial for educational attainment.)

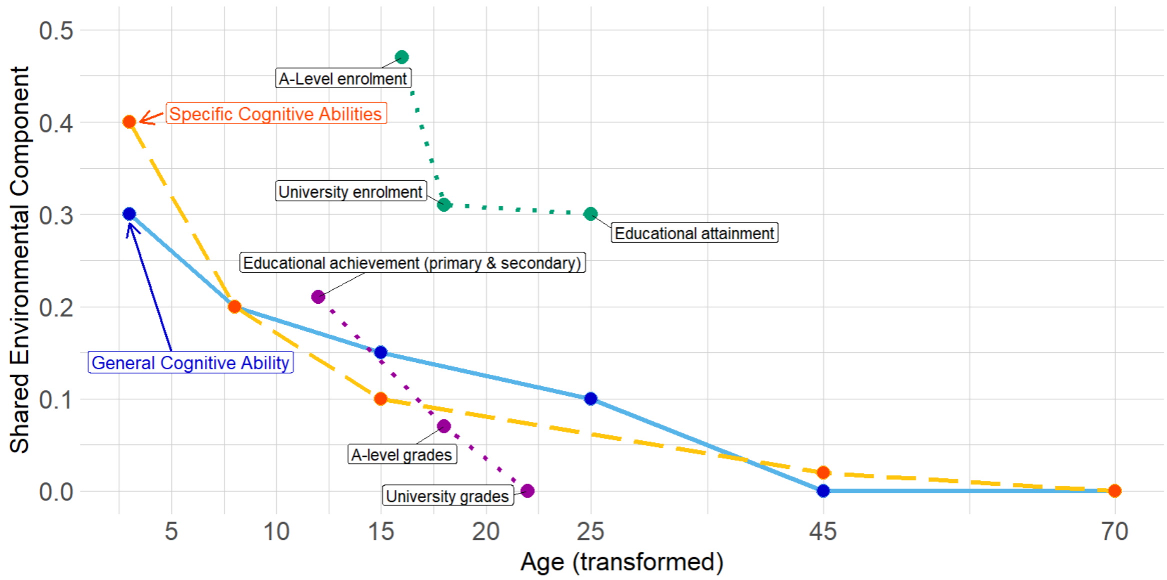
Because secondary school is mandatory in developed countries, most of the variance in educational attainment comes from whether individuals go to university [38]. Although educational attainment can only be assessed in adulthood, it is the outcome of performance and choices in secondary school. In the UK, going to university depends on making the decision to pursue university education by enrolling in the requisite A-level course at age 16. A-level enrolment showed the highest shared environmental estimate (47%) of all education-related variables [33]. The subsequent decision to actually enrol at university also showed substantial shared environmental influence (36%) [34]. It seems likely that these gatekeepers for going to university are responsible for the shared environmental influence on educational attainment.

We conclude that, although environmental influences shared by parents and their offspring have only a modest effect on educational attainment, environmental influences shared by siblings, which include parental effects independent of their educational attainment, have a substantial impact (about 30%). Although this conclusion about educational attainment might seem at odds with the conclusion that shared environmental influences for cognitive traits disappear in adulthood, educational attainment is the result of shared environmental influences on diverging pathways in adolescence that lead to tertiary education. In other words, shared environmental influence on adult educational attainment reflects the lasting effects of shared environment in adolescence rather than experiences in adulthood.

Implications

Three conclusions emerge from these findings, as illustrated in Figure 5. First, shared environmental influence for general and specific cognitive abilities declines from about 30% in childhood to 10% in adolescence and to 0% by early adulthood. Second, for educational achievement, estimates of shared environment are about 20% throughout primary and secondary school but disappear in tertiary education. Third, what stands out is the substantial estimate of shared environment for the decision to take the two-year A-level preparatory course for university (47%), which drives shared environmental influence on the decision to enrol at university (31%) and, ultimately, on educational attainment (30%).

Figure 5. Summary of shared environmental estimates for cognitive traits in childhood, adolescence, and early adulthood. For interpretability, ages 30-70 have been scaled to fit into a compressed range, equivalent in width to that of ages 0-25.



In other words, for cognitive traits, moderate shared environmental influence is found in childhood when children live at home under the influence of their parents and attend the same schools, but the influence of shared environment disappears by late adolescence as young people make their own way in the world. The only exception is educational attainment, which is nonetheless driven by decisions made in adolescence to go to university. In summary, environmental influences that affect cognitive traits in adulthood are nonshared. In adulthood, the phrase *cognitive traits* is limited to cognitive abilities rather than educational achievement because formal education typically ends in early adulthood.

This finding has far-reaching implications for science and society. Understanding environmental influences on cognitive abilities, society's true intellectual capital, is important because their societal impact emerges as young people enter the workforce. Yet hardly anything is known about these nonshared experiences. One reason for this lack of knowledge is that nearly all research on the environmental causes of cognitive differences has assumed these influences are shared [39], an assumption that our review indicates is wrong.

What are the nonshared experiences responsible for differences in cognitive abilities among adults? Any experience in adulthood can be considered as a source of nonshared environmental influence, including accidents, illnesses, further education, self-improvement, jobs, parents, spouses, friends, peers, social media, sports, and religion. Two general methods are available for identifying nonshared environmental effects controlling for genetic and shared environmental effects. The touchstone for identifying nonshared environmental influences is differences within pairs of identical twins. Because identical twin pairs inherit identical DNA, their cognitive differences can only be due to nongenetic factors that make siblings different, thus bypassing genetic confounding. Another method is multivariate genetic analysis which can parse correlations between environmental measures and cognitive abilities into genetic, shared environmental, and nonshared environmental components. Neither of these approaches has been used to identify nonshared environmental influences on cognitive abilities in adulthood.

Although there are many candidates for nonshared environmental influence on cognitive abilities in adulthood and methods exist to confirm their candidacy, two sets of findings bode ill for this enterprise. The first omen is that 30 years of research trying to identify the causes of nonshared environment for psychopathology and personality in a line-up of the usual suspects, especially parenting, has not identified the culprits [40]. This research on the usual suspects is analogous to the candidate-gene phase of genomics in the 1990s, which investigated a handful of genes thought to be associated with a trait. With the advent of genome-wide association analysis, the candidate-gene approach was superseded by genome-wide association, a polygenic model that recognised that the ubiquitous heritability of complex traits is caused by many genetic variants with very small effect sizes [41]. Similarly, nonshared environment might be due to many events each with very small effect size, a 'poly-environmental' model, which is becoming feasible with technological advances that can capture micro-environmental events in real time, such as wearable devices and online footprints [42]. It is an empirical issue, not yet investigated, whether these new technologies can capture experiences that systematically predict nonshared environmental effects on cognitive abilities in adulthood after controlling for gene-environment correlation.

The second omen is that nonshared environmental influences on cognitive traits appear to be unstable. From childhood through adolescence, longitudinal twin studies indicate that age-to-age stability of educational achievement and general cognitive ability is primarily due to genetics and secondarily to shared environmental influences [31,21]. Nonshared environment contributes to age-to-age change, not continuity. In other words, nonshared experiences that impact cognitive abilities in adulthood are not the residue of nonshared experiences earlier in life. Although longitudinal genetic research on cognitive abilities in adulthood is scarce [43], extant research suggests that genetics accounts for stability and nonshared environment contributes to age-to-age change in adulthood [44,45]. In contrast, the search for nonshared environmental influences for psychopathology and personality has assumed long-lasting effects, for example, investigating environmental factors responsible for the differences in stably discordant pairs of identical twins.

Are these unstable nonshared environmental effects merely error of measurement? Although there are many approaches to measurement error, the most conservative is short-term test-retest reliability, which indexes error as change [46]. Cognitive abilities, especially intelligence tests, are highly reliable, with two-week test-retest reliabilities exceeding 0.90 [47], which means that measurement error so defined accounts for less than 10 percent of the variance. If the variance of cognitive abilities is attributed 50% to genetics, 0% to shared environment, and 10% to measurement error, then nonshared environment accounts for the remaining 40% of the variance beyond short-term measurement error.

A reconceptualisation of nonshared environmental factors that can address this instability begins with the proposition that they are random [40], which has been usefully defined as unpredictability [48]. Accidents and illnesses are classic examples of random sources of nonshared environmental influence that can make identical twins different. Micro-environments are also likely to appear random in the sense of being unpredictable. These random factors can have short-term as well as long-term effects; they could even reclaim some of what we call test-retest unreliability as nonshared environmental effects.

The second component of this reconceptualisation adds randomness to the consideration of endogenous processes. The search for nonshared environmental influences has focused on exogenous events external to the individual such as parenting, accidents, and micro-environments. Instead, random endogenous noise generated by complex biological systems independent of exogenous events has been proposed as the major source of nonshared environmental influence, summarised as 'the intrinsic stochasticity of molecular processes' [49]. The best example of a random endogenous nonshared environmental process that differs within pairs of identical twins is somatic mutations, noninherited mutations that can occur with each cell division [50]. However, noise can come from any endogenous process, such as stochastic developmental changes in neuroanatomical structures [51,52] and epigenetics [53,54], as well as psychological processes [40], although proving that these are random events with causal effects is difficult. Nevertheless, randomness has increasingly been documented in fundamental processes throughout science [55], including physics [56], economics [57], and sport [58].

A general scientific implication of this radical reconceptualization of nonshared environment is the need to transition from scientists' strongly held belief in determinism [59] to a probabilistic perspective that embraces randomness [60,61]. Although randomness limits our ability to predict and control the nonshared environmental causes of individual differences in cognitive abilities in adulthood, we can at least understand the processes, such as biological noise, by which nonshared environment has its effects. Because multiple random processes are unlikely to have the same pattern of effects across individuals, this understanding might require shifting from nomothetic strategies that look for average effects in the population to idiographic approaches that investigate idiosyncratic experiences [62]. It may be possible to extract nomothetic patterns from large samples of idiographic data using artificial intelligence.

A profound societal implication of this reconceptualization impacts parenting. Parents have much less control of their children's outcomes than the thousands of parenting books claim, for two reasons [63]. First, genetics is the major systematic force making children who they become as adults, but parents do not control their genetic endowment to their children. The second reason is specific to this review: parents do not have the levers to control how their children turn out as adults if nonshared environmental effects are random. While an absence of parenting altogether would manifest as neglect, differences in the normal variation of parenting do not appear to contribute towards systematic differences in behavioural outcomes in their children. The cognitive domain offers some consolation in the finding that shared environmental factors, presumably parents and teachers, make a difference in their children's cognitive abilities and educational achievement, although these effects wane in adolescence and disappear in adulthood. One outcome for which shared environment has a substantial effect lasting into adulthood is the decision to go to university, a decision that casts a long shadow beyond educational attainment, employment, and income to encompass expanded social networks and personal growth [64,65].

This reconceptualisation also has implications for understanding our adult selves. It suggests that we are not the same person from day to day as our cognitive abilities are buffeted by random experiences beyond our control. It is difficult to accept this view because our personal experience of our cognitive strengths and weaknesses is overwhelmingly an experience of permanence. However, this sense of stability occurs because genetics is the systematic, stable force responsible for individual differences in cognitive abilities in adulthood after the impact of earlier shared environment has disappeared. Nonetheless, nonshared experiences during adulthood account for nearly as much of the variance as genetics. The neuroscience of consciousness [66] and mindfulness [67] could be helpful in understanding these random transient experiences – for example, endogenous cognitive noise emanating from attention, motivation, and emotions – as they affect our cognitive abilities in adulthood.

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Supplementary Information

This section includes material that was too much to include in the text within the journal's word limit.

Supplementary Information 1: General cognitive ability

The 1987 review of nonshared environment [1] concluded that, in contrast to psychopathology and personality, shared environmental influence on general cognitive ability (g) is substantial as indicated by twin and adoption studies. For example, the average weighted twin correlation in 34 studies reported before the 1980s was 0.85 for identical twins (4672 pairs) and 0.58 for fraternal twins (5533 pairs) [2]. This pattern of twin correlations suggested that about 30% of the variance of general cognitive ability can be attributed to environmental influences shared by twin siblings.

However, the 1987 review also mentioned that 'recent data suggest that environmental variance that affect IQ is also of the nonshared variety *after adolescence*' [1] (p.1). Subsequent research has consistently confirmed this hypothesis. As shown in Figure 1 in the text, a 2015 meta-analysis of twin studies of 'higher-level cognitive functions' [3] and a mega-analysis of standard measures of g estimated shared environment as about 30% in childhood, about 10-15% in adolescence, and near 0% in adulthood [4].

It should be noted that two factors could inflate twin study estimates of shared environment. The first is parental assortative mating, which is substantial for general cognitive ability, with spouse correlations of about 0.40 [5]. Genetic effects of assortative mating increase fraternal twin correlations but cannot increase identical twin correlations because they are already identical genetically. In twin analyses, this increase in fraternal twin correlations will inflate estimates of shared environmental influence. The second factor is environments shared by twins that are not shared by nontwin siblings, as indicated by fraternal twin correlations that exceed correlations for nontwin siblings [6]. These special twin environments could include prenatal experiences of sharing the same womb at the same time and postnatal experiences of growing up at the same time.

Nonetheless, confirmation of the importance of shared environmental influence on g in childhood and its decline in adolescence comes from the most powerful design for estimating shared environment effects: adoptive siblings. In 1978, Scarr and Weinberg reported the results of a study of 104 pairs of adoptive siblings that found a correlation of -.03 for *g* [7]. Although this finding might have just been a quirk, this was the first study of post-adolescent adoptive siblings, 16 to 22 years old. Until that time, no one had noticed that the correlation of 0.30 for adoptive siblings in earlier studies was based on pre-adolescent children. Scarr and Weinberg hypothesized that shared environment is important when children are living at home but fades in importance as adolescents increasingly make their own way in the world. When this hypothesis was mentioned in the 1987 review of nonshared environment, commentators expressed disbelief [8,9]. However, as described in the text, studies of post-adolescent adoptees consistently confirmed this result, showing an average correlation near zero for post-adolescent adoptive siblings. In contrast, pre-adolescent adoptive siblings yielded an average correlation of about 0.25 [10].

A more recent longitudinal study of adoptive siblings provided the strongest evidence for the decline of shared environmental influence. In a study of up to 215 adoptive families, the g correlation for genetically unrelated siblings was 0.33 at the average age of 8 but only 0.02 when they were tested again 10 years later [11]. A model-fitting analysis of all adoptive and nonadoptive families in this study including parents and siblings at the older age yielded an estimate of zero for shared environmental influence on g. Another recent study of 404 pairs of adoptive siblings found a correlation of 0.17 for g [12]. This correlation is halfway between the estimates of 0.02 and 0.33, which makes sense because the adoptive siblings in this study had a wide age range spanning adolescence and early adulthood with most participants under 18. However, a longitudinal study with eight waves of assessment from 1 to 16 years of age also reported a more moderate average correlation of only 0.16 for 59 to 128 adoptive sibling pairs with little developmental change [13], which suggests that the estimate of one-third shared environmental influence in childhood [11] might be on the high side.

As indicated in the text, the parent-child adoption design yields mixed results, with recent adoption studies reporting near-zero g correlations between adoptive parents and their adopted children. However, this parent-child design only assesses shared environmental effects of parents' g. The adoptive sibling design is a much more appropriate design because it captures all environmental effects shared by siblings growing up together in the same family.

Although the focus of our review is on the developmental decline in shared environmental influence on general cognitive ability, it is noteworthy in this context that one of the most interesting genetic findings is the corresponding increase in the heritability of general cognitive ability from about 40% in childhood to 50% adolescence to 60% adulthood [4,3].

Supplementary Information 2: Specific cognitive abilities

Specific cognitive abilities might show different developmental patterns for shared environmental influence. For example, verbal abilities, especially vocabulary, might show greater influence of shared environment than nonverbal abilities because it seems plausible that parents provide direct tuition as well as serve as models for verbal traits more so than for nonverbal traits.

In the text, two recent meta-analyses of twin data enable developmental comparisons of shared environmental influence on specific cognitive abilities [3,14]. Here we provide more detail about our use of these meta-analyses.

A 2015 meta-analysis of the world's twin literature across the life sciences [3] provided a website resource called MATCH that made it possible for us to extract average twin correlations for specific cognitive abilities. To boost sample sizes and to simplify presentation, the MATCH application summarised weighted average twin correlations at the level of 28 broad categories of traits throughout the biological sciences such as skeletal, metabolic, dermatological, cardiovascular, neurological, and cognitive traits. Within the cognitive category, twin results can be extracted at the level of general 'functions' for verbal ability, numerical ability, and memory. For example, what we refer to as verbal ability is a grouping called 'mental functions of language', which includes 105 measures of receptive, expressive, and integrative language functions. The MATCH website can be used to estimate shared environmental effects by age for these general groupings of specific cognitive abilities.

In the text, Figure 2 summarizes twin study estimates of shared environment across four ages for verbal ability, numerical ability, and memory. Details about twin correlations and sample sizes follow.

Table 1 for Supplementary Information 2: Twin study details for Figure 2 in the text.

Trait	Age	N/pairs MZ	N/pairs DZ	rMZ	rDZ	A	C	E
Verbal Ability	0-11	36827	48243	0.725	0.475	0.500	0.225	0.275
Verbal Ability	12-17	10331	14159	0.65	0.417	0.466	0.184	0.35
Verbal Ability	18-64	561	726	0.538	0.284	0.508	0.030	0.462
Verbal Ability	65+	392	253	0.65	0.190	0.650	0.000	0.350
Numerical Ability	0-11	26815	40795	0.704	0.414	0.580	0.124	0.296
Numerical Ability	12-17	3351	2311	0.676	0.422	0.508	0.168	0.324
Numerical Ability	18-64	NA	NA	NA	NA	NA	NA	NA
Numerical Ability	65+	NA	NA	NA	NA	NA	NA	NA
Memory	0-11	2858	1978	0.361	0.206	0.310	0.051	0.639

Memory	12-17	NA	NA	NA	NA	NA	NA	NA
Memory	18-64	2894	1342	0.527	0.184	0.527	0.000	0.473
Memory	65+	3753	2408	0.518	0.190	0.518	0.000	0.482

All three specific cognitive abilities yielded zero estimates of shared environment in adulthood and later adulthood. Verbal and numerical ability showed shared environmental influence in childhood and adolescence before declining to zero in adulthood. Memory ability was only assessed in adulthood and showed no shared environmental influence.

The 2022 review [14] investigated specific cognitive abilities at a more refined level of analysis. Cognitive measures used in adequately powered twin studies were grouped according to the Cattell-Horn-Carroll (CHC) hierarchical model of intelligence [15]. The middle level of the CHC model includes 16 categories such as reasoning, comprehension-knowledge, reading and writing, quantitative knowledge, and processing speed. The review covered 747,567 MZ-DZ twin comparisons from 77 publications with at least 140 MZ and 140 DZ twin pairs. Meta-analyses were conducted for 11 of the 16 specific cognitive abilities for which twin comparisons were available. The published meta-analysis reported heritability estimates as a function of age but not estimates of shared environment. We returned to the twin correlations to extract estimates of shared environment for the whole sample regardless of age and separately at five ages: 0-6, 7-11, 12-17, 18-64, and 65+, with details about twin correlations and sample sizes in the following table.

Table 2 for Supplementary Information 2: Twin study details for Figure 3 in the text.

SCA	Age	rMZ	rDZ	N/pairs	A	C	E
Auditory Processing	0-6	0.688	0.486	4083	0.404	0.284	0.312
Auditory Processing	7-11	0.470	0.341	3806	0.257	0.212	0.530
Auditory Processing	12-17	NA	NA	NA	NA	NA	NA
Auditory Processing	18-64	0.521	0.297	7707	0.449	0.072	0.479
Auditory Processing	65+	NA	NA	NA	NA	NA	NA
Comprehension-Knowledge	0-7	0.846	0.672	47526	0.348	0.498	0.154
Comprehension-Knowledge	7-12	0.790	0.504	61254	0.573	0.217	0.210
Comprehension-Knowledge	12-18	0.652	0.382	56225	0.540	0.111	0.348
Comprehension-Knowledge	18-65	0.632	0.361	4496	0.542	0.090	0.368
Comprehension-Knowledge	65+	NA	NA	NA	NA	NA	NA

Fluid Reasoning	0-8	0.814	0.678	6006	0.272	0.542	0.186
Fluid Reasoning	7-13	0.583	0.371	9267	0.426	0.158	0.417
Fluid Reasoning	12-19	0.530	0.312	18568	0.436	0.094	0.470
Fluid Reasoning	18-66	0.480	0.260	2232	0.440	0.040	0.520
Fluid Reasoning	65+	NA	NA	NA	NA	NA	NA
General Knowledge	0-9	NA	NA	NA	NA	NA	NA
General Knowledge	7-14	0.738	0.463	42170	0.549	0.188	0.262
General Knowledge	12-20	0.753	0.480	51560	0.546	0.207	0.247
General Knowledge	18-67	NA	NA	NA	NA	NA	NA
General Knowledge	65+	NA	NA	NA	NA	NA	NA
Long-term Memory	0-10	0.608	0.374	2084	0.466	0.141	0.392
Long-term Memory	7-15	NA	NA	NA	NA	NA	NA
Long-term Memory	12-21	NA	NA	NA	NA	NA	NA
Long-term Memory	18-68	NA	NA	NA	NA	NA	NA
Long-term Memory	65+	NA	NA	NA	NA	NA	NA

Quantitative Knowledge	0-11	NA	NA	NA	NA	NA	NA
Quantitative Knowledge	7-16	0.719	0.409	91678	0.618	0.100	0.281
Quantitative Knowledge	12-22	0.773	0.432	42902	0.681	0.092	0.227
Quantitative Knowledge	18-69	NA	NA	NA	NA	NA	NA
Quantitative Knowledge	65+	NA	NA	NA	NA	NA	NA
Reading and Writing	0-12	0.722	0.498	8739	0.447	0.275	0.278
Reading and Writing	7-17	0.751	0.431	125360	0.641	0.110	0.249
Reading and Writing	12-23	0.677	0.393	36085	0.569	0.109	0.323
Reading and Writing	18-70	0.636	0.340	1984	0.592	0.044	0.364
Reading and Writing	65+	NA	NA	NA	NA	NA	NA
Processing Speed	0-13	NA	NA	NA	NA	NA	NA
Processing Speed	7-18	0.551	0.289	3661	0.524	0.027	0.449
Processing Speed	12-24	0.744	0.349	1746	0.744	0.000	0.256
Processing Speed	18-71	NA	NA	NA	NA	NA	NA
Processing Speed	65+	NA	NA	NA	NA	NA	NA

Short-term Memory	0-14	0.467	0.286	2388	0.361	0.106	0.533
Short-term Memory	7-19	0.379	0.211	12501	0.337	0.042	0.621
Short-term Memory	12-25	0.494	0.224	8039	0.494	0.000	0.506
Short-term Memory	18-72	0.456	0.257	7165	0.397	0.059	0.544
Short-term Memory	65+	0.358	0.172	4900	0.358	0.000	0.642
Reaction and Decision Speed	0-15	NA	NA	NA	NA	NA	NA
Reaction and Decision Speed	7-20	NA	NA	NA	NA	NA	NA
Reaction and Decision Speed	12-26	0.492	0.233	4356	0.492	0.000	0.508
Reaction and Decision Speed	18-73	0.240	0.110	1816	0.240	0.000	0.760
Reaction and Decision Speed	65+	NA	NA	NA	NA	NA	NA
Visual Processing	0-16	0.551	0.386	15097	0.331	0.221	0.449
Visual Processing	7-21	0.722	0.420	23227	0.603	0.119	0.278
Visual Processing	12-27	0.499	0.198	3138	0.499	0.000	0.501
Visual Processing	18-74	0.460	0.234	20172	0.453	0.007	0.540
Visual Processing	65+	0.571	0.335	1775	0.471	0.099	0.429

Specific Cognitive Abilities (mean)	0-17	0.778	0.591	85923	0.374	0.404	0.222
Specific Cognitive Abilities (mean)	7-22	0.732	0.431	372924	0.602	0.130	0.268
Specific Cognitive Abilities (mean)	12-28	0.688	0.402	222619	0.571	0.117	0.312
Specific Cognitive Abilities (mean)	18-75	0.491	0.263	45572	0.456	0.035	0.509
Specific Cognitive Abilities (mean)	65+	0.423	0.215	6675	0.415	0.008	0.577

Although the review included nearly 750,000 twin comparisons, data were scarce, or missing altogether, when divided by five ages and 11 cognitive traits. Nonetheless, some trends emerged, as shown in Figure 3 in the text. Like the results of the 2015 meta-analysis [3], the estimates of shared environment showed a general downward developmental trend, with all traits yielding estimates less than 10% in adulthood.

In early childhood, shared environmental estimates were extremely high for Comprehension-Knowledge (50%) and Fluid reasoning (54%), but these estimates declined sharply in middle childhood (22% and 16%) and adolescence (11% and 9%), and remain low in adulthood (9% and 4%). Three other cognitive abilities that show substantial shared environmental influence in early childhood are Reading and Writing (28%), Auditory Processing (28%), and Visual Processing (22%); these estimates of shared environment also decline to less than 10% by adulthood. A probable methodological reason for the high estimates of shared environment in early childhood is that the measures in early childhood rely on parent reports rather than test results [16]. When one parent rates both twins, twin correlations are likely to be inflated, which will be read as shared environmental influence in twin analyses.

The text notes that insufficient data for adoptive siblings is available to test the hypothesis of declining influence of experiences shared by siblings. The only sibling adoption study in childhood reported model-fitting estimates of shared environmental estimates of 0.06 for verbal, 0.26 for spatial, 0.00 for perceptual speed, and 0.14 for memory at ages 3 and 4 for about 50 adoptive and 50 nonadoptive sibling pairs [17]. A study of adoptive siblings at the average age of 13 found no evidence for shared environmental influence for the same four cognitive abilities, with an average adoptive sibling correlation of 0.02 for 52 pairs [18]. In two other studies of adoptive siblings, the average age of the siblings was 18, an age when we would not expect to find evidence for shared environmental influence for g. The results confirm this expectation for specific cognitive abilities. In one study, the average adoptive sibling correlation was 0.03 for 17 IQ subtests for 100 pairs of adoptive siblings [19,11]. In the other study, the average adoptive sibling correlation was 0.05 for four IQ subtests for 84 pairs of adoptive siblings [7].

The text indicates that three studies using the parent-child adoption design with specific cognitive ability data yielded an average correlation of 0.03 between adoptive parents and their adopted children across childhood and adolescence. The largest adoption study focused on specific cognitive abilities from early childhood through adolescence is the longitudinal Colorado Adoption Project (CAP) [20]. CAP included 245 children adopted away from their biological parents at birth, their adoptive and biological parents, and matched nonadoptive families who share both genes and environment. The average correlations between adoptive parents and their adopted children across eight ages from 3 to 16 were 0.05 for verbal, 0.01 for spatial, -0.03 for perceptual speed, and 0.03 for recognition memory. At age 16, data from adopted children, their biological and adoptive mothers and fathers, and matched nonadoptive families were analysed simultaneously in a model-fitting approach. Estimates of shared environmental transmission from parents to offspring were 2% for verbal ability, 1% for spatial, 6% for perceptual speed, and 5% for memory. Another adoption study with 250 adoptive families also reported low correlations between adoptive parents and their adopted children at age 18 [19],[11]. For the 11 subscales of an IQ tests, the average correlation was 0.03. A third study found an average correlation of 0.07 for four IQ subtests in a study of 104 adoptive families [7].

Supplementary Information 3: Educational achievement

The text mentions that educational achievement is meant to assess what is taught at school, in contrast to cognitive abilities which connote inherent intellectual capabilities. Tests of school performance, for example literacy and numeracy, usually assess both achievement and ability. That is, they assess both what has been learned and how well students can use this basic knowledge. The CHC hierarchical model of intelligence mentioned in the previous section on specific cognitive abilities [15] includes reading and writing and quantitative knowledge as cognitive abilities because these traits are usually assessed more as abilities than achievement. As shown in Figure 3 in the text, literacy and numeracy assessed as abilities yielded shared environmental results like other cognitive abilities, showing some shared environment in childhood that diminishes to less than 10% in adulthood.

Twin studies using national tests of educational achievement point to substantial shared environmental influence. A US national test administered at age 13 assessed four domains of school performance enabled a study of 2164 twin pairs across four domains -- English usage, mathematics, social studies, and natural science. This classic twin study in the 1960s yielded a 30% estimate of shared environmental influence [21]. A more recent UK twin study reported a shared environment estimate of 29% for a total score on a UK national test of educational achievement at age 16 for 5008 twin pairs [22]. However, a Dutch study yielded an estimate of only 8% for a total score on a national test administered at age 12 in a study of 7020 twin pairs [23], although an earlier Dutch study using the same test at the same age yielded an estimate of 27% based on a sample of 691 twin pairs [24].

A dozen other smaller twin studies yielded a wide range of estimates of shared environment in part because they were underpowered to provide reliable point estimates of shared environment and in part because of study-specific problems such as estimating zygosity indirectly from the ratios of same-sex versus opposite-sex twins [25].

The text indicates that twin study estimates of shared environmental influence did not differ much across subjects or from the early school years to secondary school. The following table provides details of these studies.

Table for Supplementary Information 3: Twin study details for educational achievement across subjects and ages.

Study	Trait	Age	N MZ	N DZ	rMZ (95% CI)	rDZ (95% CI)	C (95% CI)	Estimate
Rimfeld et al. (2018)	English	7	1858	3082	.85 (.84-.86)	.48 (.46-.50)	.10 (.05-.15)	Model-Fitting
Rimfeld et al. (2018)	English	11	1870	3144	.82 (.81-.84)	.51 (.49-.54)	.19 (.14-.24)	Model-Fitting
Rimfeld et al. (2018)	English	14	426	657	.86 (.83-.88)	.54 (.48-.59)	.19 (.08-.29)	Model-Fitting
Rimfeld et al. (2018)	English	16	2250	3962	.83 (.81-.84)	.54 (.51-.55)	.24 (.19-.28)	Model-Fitting
Rimfeld et al. (2018)	Maths	7	1858	3081	.76 (.74-.78)	.47 (.45-.50)	19 (.14-.24)	Model-Fitting
Rimfeld et al. (2018)	Maths	11	1889	3160	.84 (.83-.86)	.46 (.43-.49)	.07 (.02-.13)	Model-Fitting

Rimfeld et al. (2018)	Maths	14	437	671	.70 (.65-.75)	.45 (.39-.51)	.18 (.06-.29)	Model-Fitting
Rimfeld et al. (2018)	Maths	16	2217	3922	.82 (.81-.84)	.52 (.50-.54)	.23 (.17-.26)	Model-Fitting
Rimfeld et al. (2018)	Science	7	NA	NA	NA	NA	NA	Model-Fitting
Rimfeld et al. (2018)	Science	11	1893	3178	.78 (.76-.80)	.50 (.47-.52)	.21 (.16-.27)	Model-Fitting
Rimfeld et al. (2018)	Science	14	437	665	.54 (.47-.60)	.31 (.24-.38)	.06 (.01-.20)	Model-Fitting
Rimfeld et al. (2018)	Science	16	2056	3535	.83 (.81-.84)	.54 (.52-.56)	.25 (.21-.30)	Model-Fitting
De Zeeuw et al. (2016)	Arithmetic	6-7	341	0.449	0.664	0.449	0.234	Falconer's
De Zeeuw et al. (2016)	Arithmetic	7-8	302	0.428	0.667	0.428	0.189	Falconer's

De Zeeuw et al. (2016)	Arithmetic	8-9	301	0.397	0.659	0.397	0.135	Falconer's
De Zeeuw et al. (2016)	Arithmetic	9-10	224	0.447	0.704	0.447	0.190	Falconer's
De Zeeuw et al. (2016)	Arithmetic	10-11	212	0.32	0.727	0.320	0.000	Falconer's
De Zeeuw et al. (2016)	Arithmetic	11-12	119	0.544	0.645	0.544	0.443	Falconer's
De Zeeuw et al. (2016)	Reading	7-8	194	175	0.822	0.434	0.046	Falconer's
De Zeeuw et al. (2016)	Reading	8-9	199	182	0.733	0.382	0.031	Falconer's
De Zeeuw et al. (2016)	Reading	9-10	147	150	0.774	0.520	0.266	Falconer's
De Zeeuw et al. (2016)	Reading	10-11	145	125	0.849	0.545	0.241	Falconer's

De Zeeuw et al. (2016)	Reading Comprehension	8-9	305	285	0.667	0.407	0.147	Falconer's
De Zeeuw et al. (2016)	Reading Comprehension	9-10	232	219	0.710	0.513	0.316	Falconer's
De Zeeuw et al. (2016)	Reading Comprehension	10-11	228	215	0.649	0.417	0.185	Falconer's
De Zeeuw et al. (2016)	Reading Comprehension	11-12	167	147	0.649	0.484	0.319	Falconer's
De Zeeuw et al. (2016)	Spelling	6-7	344	316	0.623	0.399	0.175	Falconer's
De Zeeuw et al. (2016)	Spelling	7-8	320	283	0.648	0.405	0.162	Falconer's
De Zeeuw et al. (2016)	Spelling	8-9	311	285	0.689	0.329	0.000	Falconer's
De Zeeuw et al. (2016)	Spelling	9-10	234	225	0.699	0.446	0.193	Falconer's

De Zeeuw et al. (2016)	Spelling	10-11	224	211	0.704	0.306	0.000	Falconer's
De Zeeuw et al. (2016)	Spelling	11-12	166	141	0.721	0.483	0.245	Falconer's
De Zeeuw et al. (2016)	Arithmetic	11-12	757	787	0.700	0.374	0.048	Falconer's
De Zeeuw et al. (2016)	Language	11-12	757	787	0.765	0.457	0.149	Falconer's
De Zeeuw et al. (2016)	Info skills	11-12	755	786	0.633	0.375	0.117	Falconer's
De Zeeuw et al. (2016)	Science and social studies	11-12	668	695	0.745	0.515	0.285	Falconer's
De Zeeuw et al. (2016)	Total score (all subjects)	11-12	1112	1129	0.804	0.468	0.132	Falconer's
De Zeeuw et al. (2015)	Reading	6-13	5330	7084	NA	NA	0.100	Model-Fitting

De Zeeuw et al. (2015)	Reading Comprehension	6-14	3042	5218	NA	NA	0.130	Model-Fitting
De Zeeuw et al. (2015)	Maths	6-15	3419	6247	NA	NA	0.100	Model-Fitting
De Zeeuw et al. (2015)	Language	6-16	2740	4951	NA	NA	0.150	Model-Fitting
De Zeeuw et al. (2015)	Spelling	6-17	1093	1692	NA	NA	0.230	Model-Fitting
De Zeeuw et al. (2015)	Educational Achievement	6-18	4341	7808	NA	NA	0.120	Model-Fitting

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A Danish adoptive sibling study of educational achievement confirmed these twin study estimates of shared environmental influence [26]. At the end of primary school, average scores on a national examination yielded a correlation of 0.24 for 534 adoptive sibling pairs. In addition, adoptive siblings correlated 0.30 for enrolment in an academic high school. This adoption study also showed that adoptive parents' educational attainment correlated only 0.05 for mothers and 0.11 for fathers with their adopted children's educational achievement.

These findings suggest that siblings share environmental influences that affect their school performance, but parents' educational attainment has little shared environmental effect.

Supplementary Information 3: Educational attainment

As indicated in the text, meta-analyses of twin data consistently yield estimates of shared environmental influence for educational attainment greater than 30% [27,28].

Two issues cloud this conclusion from twin studies. First, fraternal twins are more similar than nontwin siblings for educational attainment (0.55 versus 0.44), suggesting that the twin design inflates estimates of shared environment by including shared environment of about 10% that is specific to twins [29], as is also the case for g [6]. The second issue is assortative mating, which is exceptionally high for educational attainment. The average spouse correlation for educational attainment was 0.57 in a mega-analysis of 23,705 couples [27] and 0.53 in a meta-analysis of 27 studies with 230,915 couples [30], substantially higher than the spouse correlation of 0.39 for g in a meta-analysis of 2,562 couples in 10 studies [30].

Assortative mating has been reported to be responsible for most of the shared environment for educational attainment as estimated in twin studies in an analysis of an Australian sample of 3808 twin pairs [31], in an analysis of 937 German twin pairs [29], and in a children-of-twins analysis of 4424 Swedish families [32]. On the other hand, another analysis of the same Australian data set found only a modest effect of assortative mating [33], as did two US studies [34,12].

The effect of assortative mating is a complicated matter, inspiring the first attempts at structural equation model fitting in 1921 [35], but one critical issue is that these analyses assume that the effects of assortative mating are mediated genetically. However, the genomic spouse correlation accounts for only a minor portion of assortative mating for educational attainment [36,37]. In contrast, a shared environmental explanation has been called 'the obvious hypothesis': university-educated couples use their resources including being role models to foster their children's university enrolment [38].

Given the complexity of the effects of assortative mating in relation to shared environmental estimates from the twin design, it is surprising that little attention has been paid to adoption studies. Especially relevant is the adoptive sibling design which captures the net shared environmental effect of growing up in the same family, but without genetic effects of assortative mating. However, we found only one adequately powered study of educational attainment in adoptive siblings, a US study of 409 adoptive sibling pairs [12]. Nonetheless, the correlation between these adoptive siblings for educational attainment was 0.37, which strongly supports the substantial shared environment estimate from twin studies.

More research is available for adoptive parents and their adopted children, but, as discussed previously, this design is limited to transgenerational shared environmental influence of educational attainment. The correlation between educational attainment of adoptive parents and their adopted children was only 0.09 in a Swedish study of 2125 adopted children [39], 0.03 in another Swedish study of 4893 foreign-born adopted children [40], and 0.12 for 4556 adoptees in Taiwan [41]. Mixed results have been reported in smaller US studies:

0.04 (N = 128) [42], 0.19 (N = 170) [42], 0.15 (N = 322) [11], and 0.28 (N = 369) [43]. The average weighted correlation for educational attainment of adoptive parents and their adopted children is 0.08, indicating that parents' educational attainment has little shared environmental effect on their children's educational attainment.

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