Skill Formation with Siblings

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Abstract

This paper estimates a structural model of skill formation for children who grow up with siblings, introducing a novel variable, the "sibling bond," which captures how well siblings get along. Using data from the Millennium Cohort Study in the United Kingdom, I construct this measure from information on the frequency and quality of sibling interactions, such as enjoying playtime together and teasing each other. Descriptive evidence shows that a stronger sibling bond is associated with better child outcomes during adolescence. The structural estimates are consistent with the sibling bond being a productive input in the skill formation of both younger and older siblings, alongside parent-child interactions.

JEL codes: J24, I24, I28, J13, O15.

Keywords: Human Capital; Skills; Education and Inequality; Siblings; Family.

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1 Introduction

More than 75% of children in the United Kingdom have at least one sibling by the age of 5 according to the 2006 wave of Millennium Cohort Study (MCS) data. Similarly, in the United States, 82% of youth aged 18 and under lived with at least one sibling according to the Current Population Survey.[1] As siblings grow up together, they experience everyday interactions and extensive contact, serving as sources of social support and role models for one another. However, relatively little attention has been paid to how the relationship and interactions between siblings could be relevant to learning and development, compared to the wealth of studies on parent-child interactions (see, for example, Cunha and Heckman (2007), Currie and Almond (2011), Almond et al. (2018), Attanasio et al. (2022)).

This paper aims to contribute to the literature by bridging two strands of work: (i) estimating the technology of skill formation with an *only*-child framework and (ii) the role of siblings. The literature has estimated the technology of skill formation under an *only-child* framework, showing that parental skill and investment play an important role for child development (Cunha and Heckman, 2008; Cunha, Heckman, and Schennach, 2010; Attanasio, Cattan, Fitzsimons, Meghir, and Rubio-Codina, 2020; Attanasio, Meghir, and Nix, 2020; Caucutt, Lochner, Mullins, and Park, 2020; Agostinelli and Wiswall, 2025).[2] On the other hand, the joint production of siblings' skills within the family and its implications for understanding child development have been understudied.

The Millennium Cohort Study (MCS) data in the United Kingdom allow the construction of a novel variable, "sibling bond," which captures the quality of sibling interactions. The measure combines information on warmth and enjoyment in the sibling relationship, as well as low conflict, using questionnaire items on behaviors such as enjoying playtime together and teasing each other. A stronger sibling bond may reflect a form of relational social capital between siblings, potentially affecting development through greater cooperation, mutual support, and lower conflict. This is relevant because siblings spend nearly two more hours per week with each other in unstructured play than only children do. Such play can foster cognitive, physical, and socio-emotional development (Dankiw et al., 2020; Lee et al., 2020), whereas structured and educational activities are more often shared with parents (Dunifon et al., 2017).

I begin by presenting descriptive evidence that differences in the quality of the sibling bond are associated with persistent inequalities across households. First, there is a socio-economic gradient in the quality of the sibling bond. Second, a stronger bond between siblings at age 5

[1] Similar proportions of children had at least one sibling by age 5 in Ethiopia (90%), India (92%), Peru (82%), and Vietnam (77%) according to the Young Lives study. McHale et al. (2012) point out that in the United States this is a higher percentage than the percentage living in a household with a father figure (78%).

[2] Another strand of the literature has focused on understanding inequalities among siblings, focusing on the role of family size and birth order effects (see for example, Black et al. (2005)). However, it has not considered the possibility that siblings can interact and build a bond that could foster their joint development. The focus has been on parents engaging in reinforcing and compensating investment among siblings (Behrman et al., 1982; Behrman, 1988), with limited attention to the possibility that parents can also facilitate interactions and relations between siblings.

is predictive of better developmental, educational and health outcomes for the younger sibling throughout adolescence. Importantly, the richness of the MCS data allows me to show that the quality of the sibling bond is predictive of these outcomes even conditional on siblings' cognitive and socio-emotional skills, the mother-child relationship, and broader aspects of the home environment, as proxied by parental investment, parenting style, and shared family activities.

Building on this descriptive evidence, I formalize the joint production of the younger and older siblings' skills. I explicitly model the multi-dimensional nature of skills and study the formation of cognitive (ability to complete tasks and learn), internalizing (ability to focus and pursue long-term goals) and externalizing (ability to engage in interpersonal activities) skills (Achenbach, 1966; Achenbach et al., 2016). Structurally estimating the joint technology of skill formation in the presence of siblings is inherently complicated and presents two main methodological challenges: (i) measurement error in the skills and inputs and (ii) input endogeneity. After addressing these challenges, the technology of skill formation identifies two structural parameters of interest: the productivity of the sibling bond and parental investment. The main finding of the structural analysis is that, under the maintained identifying assumptions, the estimates are consistent with the sibling bond being a productive input in the skill formation of both younger and older siblings, alongside parent-child interactions.

To address the measurement error, I use the Millennium Cohort Study (MCS) data, which follow the lives of a representative sample of children born in the early 2000s in the United Kingdom. The MCS has administered a set of questionnaires to collect information on the development of the cohort member and their older sibling, as well as the quality of their interactions at the age-5 wave. I map the information recorded in the MCS questionnaires into the latent inputs and outputs of the skill formation technology through factor models (Cunha et al., 2010). This provides an effective way to summarize the information from the questionnaires and obtain an efficient measure of the latent inputs and outputs, while setting a metric for measurement and making the latent factors comparable over time and across siblings (Agostinelli and Wiswall, 2025; Freyberger, 2021).

The second challenge is the endogeneity of parental investment and sibling bond. Parents who observe a positive shock to child development, which is not observed by the econometrician, may decide to reinforce or compensate for it by adjusting their investment. A similar argument applies for a high-quality bond between siblings: children experiencing a positive shock to skills, unobserved by the econometrician, may experience fewer conflicts and more enjoyable time with their siblings. Ignoring the endogeneity of the inputs would likely bias the estimates of their productivities due to such responses to the unobserved shocks. To address this challenge, I use two exogenous shifters – local labor market shocks and adjustment costs to housing – that could affect siblings' skills only through parental investment in the first case and through the sibling bond in the second (Carneiro et al., 2013; Altonji et al., 2017; Cunha et al., 2021). These shifters are consistent with a model of parental investment in which they do not enter the siblings' production function directly, although their validity relies on exclusion restrictions that cannot be tested directly. I discuss the limitations of these assumptions in detail. Finally, the richness of the MCS data allows me to condition on an extensive set of household demographics, resources, children's socio-emotional skills, and housing arrangements, supporting the assumption that the remaining variation in the instruments is more plausibly exogenous.

This paper contributes to the literature in three main ways. First, it contributes to the literature estimating the technology of skill formation in an *only-child* framework (Cunha and Heckman, 2008; Cunha, Heckman, and Schennach, 2010; Attanasio, Cattan, Fitzsimons, Meghir, and Rubio-Codina, 2020; Attanasio, Meghir, and Nix, 2020; Agostinelli and Wiswall, 2025).[3] Families usually have more than one child and siblings interact (Francesconi and Heckman, 2016; McHale et al., 2012).[4] This paper extends the only-child framework, considers the younger and older siblings' joint technology of skill formation, and studies how parental investment and a high-quality bond between siblings affects the development of each sibling. In particular, the structural estimates are consistent with the sibling bond being a productive input in both younger and older siblings' skill formation, alongside parent-child interactions.[5]

Moreover, this paper explicitly models the multi-dimensionality of skills and considers two dimensions of socio-emotional skills (Heckman et al., 2006; Borghans et al., 2008; Heckman et al., 2018; Humphries et al., 2019; Papageorge et al., 2019; Attanasio et al., 2020, 2025). This enables me to present novel evidence on within-sibling specialization, examining whether one sibling tends to exhibit stronger internalizing skills when the other displays stronger externalizing skills, and vice versa (Plomin and Daniels, 1987). Examining cognitive, externalizing and internalizing skills also underscores the complexity of skill formation, as different types of skills may develop through distinct processes.

Second, there is a growing interest in understanding the role played by siblings, which has mostly focused on quantifying sibling spillovers, while noting that identifying them is difficult. This paper contributes to this literature by directly measuring the strength of the sibling bond and estimating how variation in the sibling bond affects child development within a structural model. Previous papers have not made direct attempts to measure the strength of the sibling bond, even though a strong sibling bond could strengthen sibling spillovers. For example, Altonji et al. (2017) assess the extent to which the correlations in substance use between siblings are causal.

[3]Other examples of estimates for the production function with an *only* child are Fiorini and Keane (2014), Attanasio et al. (2017), Moroni et al. (2019), Agostinelli et al. (2019), Attanasio et al. (2020), Gensowski et al. (2020), Houmark et al. (2020), Caucutt and Lochner (2020), Aucejo and James (2021), and Carneiro et al. (2022). Pavan (2016) estimates the technology of skill formation to understand the birth order effect in cognitive skill, but does *not* allow siblings to spend time together and interact with each other.

[4]Del Boca et al. (2014) and Gayle et al. (2015) estimate a structural model with more than one child, where they allow parents to spend time with both children at the same time, but do not allow for sibling interactions and assume that parents know the structure of the production function. Also, Cunha et al. (2013), Boneva and Rauh (2018) and Attanasio et al. (2019) have shown that parents have biased beliefs about the returns to investment.

[5]Siblings may act as important team players, who can help each other achieve common goals within the family, such as their joint production of skills. The importance of teamwork within the family is still understudied, while it has been shown to matter, for example, within the firm (Weidmann and Deming, 2021).

Altmejd et al. (2021) provide evidence from Chile, Croatia, Sweden, and the United States that older siblings affect the college and major choice of the younger sibling.[6]

Third, estimating the joint technology of skill formation complements the literature on the trade-off between the quantity and quality of children, which examines if parents decrease their investments per child when increasing the quantity of children (Becker and Lewis, 1973; Willis, 1973; Becker and Tomes, 1976). The estimates are consistent with the possibility that positive sibling interactions partly mitigate behind the quantity-quality trade-off (Black et al., 2005, 2010; Cáceres-Delpiano, 2006; Angrist et al., 2010; Åslund and Grönqvist, 2010; De Haan, 2010; Briole et al., 2020). Additionally, my estimates complement the literature on the birth order effects, which have been shown to explain differences in human capital among siblings (Black et al., 2005; Pavan, 2016; Lehmann et al., 2018; Breining et al., 2020). While this literature has mostly focused on showing that differences in parental investment are responsible for a birth order effect, my paper offers another explanation, emphasizing sibling interactions as another plausible mechanism.

In turn, this paper connects to the literature on intra-household inequality in human capital. This literature has mostly focused on parents engaging in reinforcing or compensating investment in response to inequality among siblings (Behrman et al., 1982; Behrman, 1988).[7] I highlight the potential for interaction between siblings, where a strong bond can foster skill development in both children. As suggested by the counterfactual simulations, this may be relevant to interventions aimed at facilitating sibling interactions by encouraging teamwork and prosocial behavior (Leijten et al., 2021).

Finally, the psychology and child development literature has also studied parent-child interactions by focusing on how environmental factors contribute to development, but now the focus is shifting to explore sibling relationships and interactions (McHale et al., 2012).[8] Similarly, the anthropology literature has investigated the role of sibling interactions for child development, highlighting that the older sibling could engage in care-taking interactions with the younger

[6]Other examples are Gurantz et al. (2020) on taking advanced placement (AP) classes in the United States, Joensen and Nielsen (2018) on choosing advanced math and science subjects in high school, Dahl et al. (2020) on choosing a field of study, Qureshi (2018) and Nicoletti and Rabe (2019) on school achievement respectively in North Carolina (USA) and England. Spillovers have been documented also related to the older sibling's cognitive skill (Dai and Heckman, 2013), the sibling's gender (Butcher and Case, 1994; Cools and Patacchini, 2019; Brenøe, 2021; Dudek et al., 2022; Jakiela et al., 2025), and having a disabled younger sibling (Black et al., 2021). Other papers have looked at sibling correlations to understand the transmission of inequality, noticing that sibling correlations are higher than parent-child correlations (Björklund et al., 2010; Vladasel et al., 2021; Björklund and Jäntti, 2020).

[7]Evidence is mixed on whether parents engage in compensating or reinforcing investments, with some studies finding evidence for reinforcing behavior (Behrman et al., 1994; Aizer and Cunha, 2012; Frijters et al., 2013; Adhvaryu and Nyshadham, 2016; Grätz and Torche, 2016), others for compensating behavior (Frijters et al., 2009; Del Bono et al., 2012; Bharadwaj et al., 2018), and some showing mixed or no effects (Ayalew, 2005; Almond and Currie, 2011; Yi et al., 2015).

[8]Similar questions about sibling interactions – measuring for example the frequency of conflicts between each sibling pair as well as how often they have fun together – are found in the Sibling Relationship Questionnaire developed in psychology by Furman and Buhrmester (1985). Some examples of studies in psychology and child development on the role of sibling interaction and direct influence on children's development outcomes are Maynard (2002), Howe et al. (2002), Stocker et al. (2002), Bank et al. (2004) and Sun et al. (2019).

sibling (see for example Weisner et al. (1977) and Lancy (2014)). Unfortunately, these studies are characterized by a small (and sometimes selected) sample and overlook the endogeneity of parental investment and sibling bond.

This paper is organized as follows. Section 2 presents the data, the descriptive evidence on the role of the sibling bond in child development, and the joint production of skills in the presence of siblings. Section 3 presents the structural estimates of the technology of skill formation for the younger and older siblings as well as the counterfactual simulations. Section 4 summarizes the results and concludes.

2 The joint production of skills with siblings

This section discusses the role of the sibling bond in the joint production of siblings' skills. First, I introduce the Millennium Cohort Study data. Second, I present the descriptive evidence on the role of the sibling bond, and explore what the sibling bond is capturing. This evidence suggests that differences in the strength of the sibling bond are associated with persistent inequalities across households. This pattern could be amplified if high-SES parents are also more likely to have multiple children (Doepke et al., 2023). Third, I extend the theoretical framework of child development to include more than one child in the family and formalize their joint production of skills, discussing how to think about the measurement of the latent inputs and outputs as well as the endogeneity of the inputs.

2.1 Data: Millennium Cohort Study

The Millennium Cohort Study (MCS) follows the lives of a representative sample of children born in the United Kingdom from the early 2000s to age 17. This paper uses data from the age-3 and age-5 waves, as information on younger and older siblings' skills is available only in these waves, while measures of the sibling bond are collected only at age 5. In the MCS, the cohort member is the younger sibling in each sibling pair. I describe each measure below in detail and present the descriptive statistics for the estimation sample in Appendix Table A1. All estimates in the paper use the Millennium Cohort Study survey weights to account for the sampling design.

Information on the younger and older siblings' socio-emotional skills comes from the Strengths and Difficulties Questionnaire (SDQ) administered at the age-3 and age-5 waves (Goodman, 1997, 2001). The SDQ is made up of five scales of five items each: (i) Emotional symptoms, (ii) Conduct problems, (iii) Hyperactivity/inattention, (iv) Peer relationship problems and (v) Prosocial behavior. Parents are asked if the cohort member and the older sibling exhibit 25 items, rating them on three levels: 'Does not apply', 'Somewhat applies', 'Certainly applies' (Appendix Table A2). Items indicating lower skills are reverse-coded so that higher values correspond to higher skills. Goodman (1997), Goodman (2001), and Goodman et al. (2010) propose adding the responses of the Conduct and Hyperactivity scales to obtain an externalizing score, and adding the responses of the Emotional and Peer Problem scales to produce an internalizing score (Achenbach, 1966; Achenbach et al., 2016).

In addition, the interviewers administer a battery of tests to the younger sibling (i.e., the cohort member child in the MCS) at ages 3 and 5, which can be used to measure cognitive skills. The tests administered at age 3 are: the Naming Vocabulary from the British Ability Scales II and the Bracken School Readiness Assessment-Revised (BSRA-R). The BSRA-R is divided into the following 6 subtests: (i) Colors (represent both primary colors and basic color terms), (ii) Letters (measure knowledge of both upper- and lower-case letters), (iii) Numbers/Counting (measure recognition of single- and double-digit numbers and assign a number value to a set of objects), (iv) Sizes (describe concepts of one, two, and three dimensions), (v) Comparisons (measure ability to match and/or differentiate objects based on one or more of their salient characteristics), and (vi) Shapes (include one, two, and three-dimensional shapes, such as linear shapes, circles, squares, triangles, cubes and pyramids). The age-5 tests comprise: (i) the Naming Vocabulary, (ii) Pattern Construction and (iii) Picture similarities from the British Ability Scales II.

Information on the sibling bond has been collected only at the age-5 wave by asking parents how often [Never, Sometimes, Frequently] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling and (iv) Teases or needles the older sibling.

Parental investment is measured at the age-5 wave by asking parents how often [Every day, Several times a week, Once or twice a week, Once or twice a month, Less often, Not at all] they do the following activities: (i) How often do you read to the child, (ii) How often tells stories to the child, (iii) How often does musical activities with the child, (iv) How often does the child paint/draw at home, (v) How often do you play physically active games with the child, (vi) How often play indoor games with the child, (vii) How often play outdoor games with the child, (viii) How often family does indoor activities together, (ix) How often child sees grandparents, (x) How often child sees other relatives, (xi) How often child spends time with friends outside school, (xii) How often ignores child when naughty, (xiii) How often smacks child when naughty, (xiv) How often shouts at child when naughty, (xv) How often sends child to bedroom/naughty chair, (xvi) How often takes away treats from child when naughty, (xvii) How often tells child off when naughty, (xviii) How often bribes child when naughty, (xix) How often tries to reason with child when naughty, (xx) How often makes sure child obeys instruction/request, (xxi) How close the bond between mother and child is.

Finally, the UK Data Service has kindly provided access to the restricted MCS data with the geo-coded location of each household via the secure lab. Each household is linked to the local employment rate between October 2004 and September 2005 in the local authority where the household resides.[9] Data on local employment in the age-5 wave are unfortunately not available for Northern Ireland.

2.2 Descriptive evidence on the sibling bond

Siblings play an important role in family life and often spend more time interacting with one another than with their parents during childhood (Dunifon et al., 2017). In particular, siblings spend nearly two additional hours per week with each other in unstructured play, which can foster cognitive, physical, and socio-emotional development (Dunifon et al., 2017; Dankiw et al., 2020; Lee et al., 2020). In contrast, structured and educational activities are more frequently shared with parents.

This section presents two motivating facts that justify the importance of the sibling bond in the study of skill formation, alongside parent-child interactions. To measure the strength of the sibling bond, I use a unique set of questions on the quality of sibling interactions, available in the age-5 wave of the MCS (Section 2.1). As a first step, to construct an index of the sibling bond, I sum the item responses and standardize the resulting index to have mean 0 and standard deviation 1.

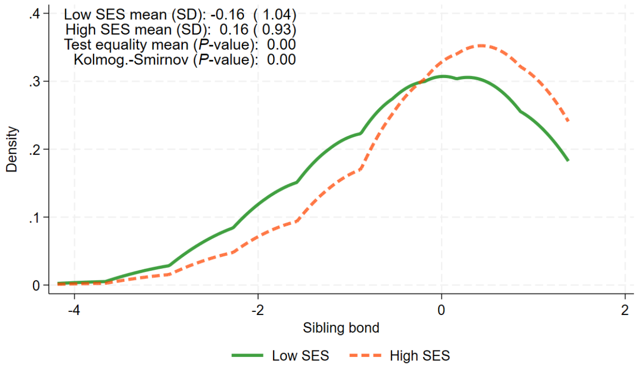
First, Figure 1 documents a socio-economic gradient in the quality of the sibling bond, with both the means and the distributions of the sibling bond being statistically different by mother's education. Similar results are found if the socio-economic status is defined as a dummy equal to 1 if the mother was smoking during pregnancy (Appendix Figure A1) and when the quality of the sibling bond is residualized by the siblings' age gap (Appendix Figure A2). Appendix Figure A3 also shows that there is a SES gradient in each item used to construct the sibling bond.

Second, Figure 2 shows that the quality of the sibling bond at age 5 predicts the younger sibling's developmental outcomes through adolescence, even after accounting for the home environment, sibling skills and a rich set of controls. In this analysis, I treat skills as multi-dimensional and distinguish three domains: cognitive (ability to complete tasks and learn), internalizing (ability to focus and pursue long-term goals) and externalizing (ability to engage in interpersonal activities) skills (Achenbach, 1966; Achenbach et al., 2016). I also control for the home environment, using measures of parental investment, parenting style, and shared activities within the household and extended family. In addition, I include information on the socio-emotional skills of both siblings and a rich set of maternal and household characteristics, including sibling characteristics, the mother's education, age, employment, mental health, household structure, housing conditions, and the closeness of the mother-child relationship. Further details on the measures and the full set of controls are provided in Section 2.1 and in the note to Figure 2.

In Figure 2, the blue dots are the point estimates from regressing the developmental outcomes

[9] Source: University of London. Institute of Education Center for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2.

Figure 1: Socio-economic gradient (mother's education) in the quality of the sibling bond

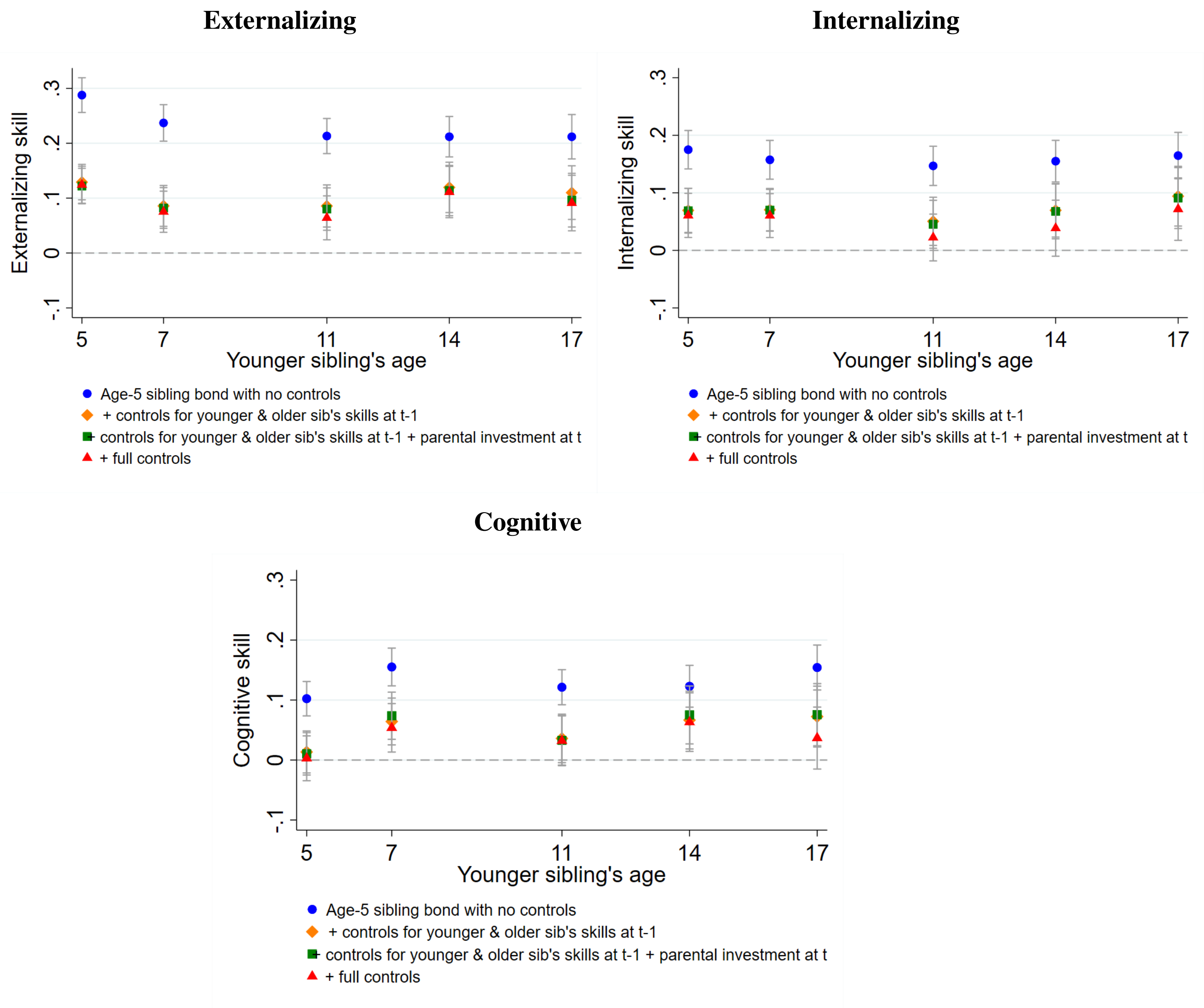


Note. The figure presents the socio-economic gradient in the quality of the sibling bond at age 5. The socio-economic status (SES) is the mother's education at the age-5 wave (dummy for whether the mother continued schooling past the minimum leaving age, based on her date of birth). The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. The index of sibling bond is standardized to have mean 0 and standard deviation 1. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). Higher scores correspond to better quality bonds. I report the means of the quality of the sibling bond by socio-economic gradient and their standard deviations (SD) between parentheses. The distribution is estimated nonparametrically, using an Epanechnikov kernel. I report the p-value of a t test on the equality of means between the two groups assuming unequal variances. I report the p-value from the Kolmogorov-Smirnov test on the equality between the distributions by socio-economic gradient.

across the younger sibling's adolescence on the age-5 sibling bond without any controls. On the other hand, the red triangles are the point estimates after conditioning on all the controls, aiming at reducing the differences in family background, home environment, and pre-existing sibling characteristics across siblings with different bond qualities. Comparing the blue dots (without controls) with red triangles (with full controls) suggests that the decline in the coefficient of the age-5 sibling bond is mostly driven by the younger and older siblings' skills in the previous wave. On the other hand, the additional controls, such as the home environment, parental resources and the mother-child bond, no longer have a substantial effect on mediating the association between the age-5 sibling bond and the younger sibling's higher development during adolescence. While some individual coefficients are statistically insignificant at certain ages, the pooled estimates presented in Appendix Table A3 suggest an overall significant association between age-5 sibling bond and later developmental outcomes across ages.

Appendix Table A4 provides additional evidence that a stronger sibling bond is predictive of better educational and health outcomes at age 17, conditional on the environmental factors discussed above. A strong sibling bond is associated with a higher grade in the English GCSE exam – a key academic milestone in the UK – and with a greater likelihood of progressing to A-levels, which are required for university entry. It is also associated with a lower probability of smoking at age 17, consistent with the psychological theory proposed by Patterson (1984), which suggests that siblings are more likely to engage in risky behaviors, such as smoking, when their relationship is marked by conflict. Although the main analysis is restricted to children who grew up with at least one sibling (75% of the sample), I also examine whether the findings are

Figure 2: Age-5 sibling bond and younger sibling's development across adolescence



Note. The figures present the point estimates and the respective confidence intervals at 95% level from regressing the younger sibling's developmental outcomes at ages 5, 7, 11, 14, and 17 on the age-5 sibling bond. The point estimates on the y-axis are in standard deviation units as the sibling bond and developmental outcomes are standardized to have mean 0 and standard deviation 1. The three dimensions of development considered are: externalizing (ability to engage in interpersonal activities), internalizing (ability to focus and pursue long-term goals) and cognitive skills (ability to complete tasks and learn). Internalizing and externalizing skills are measured with the Strengths and Difficulties Questionnaire (SDQ) (Goodman, 1997; Goodman et al., 2010). Cognitive skills are measured with a battery of tests, such as the British Ability Scales II (BAS II). The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). The parental investment index is obtained by summing the values from the questions asking the parents how often [Every day, Several times a week, Once or twice a week, Once or twice a month, Less often, Not at all] they do the following activities: (i) How often do you read to the child, (ii) How often tells stories to the child, (iii) How often does musical activities with the child, (iv) How often does the child paint/draw at home, (v) How often do you play physically active games with the child, (vi) How often play indoor games with the child, (vii) How often play outdoor games with the child, (viii) How often family does indoor activities together, (ix) How often child sees grandparents, (x) How often child sees other relatives, (xi) How often child spends time with friends outside school, (xii) How often ignores child when naughty, (xiii) How often smacks child when naughty, (xiv) How often shouts at child when naughty, (xv) How often sends child to bedroom/naughty chair, (xvi) How often takes away treats from child when naughty, (xvii) How often tells child off when naughty, (xviii) How often bribes child when naughty, (xix) How often tries to reason with child when naughty, (xx) How often makes sure child obeys instruction/request, (xxi) How close the bond between mother and child is. Full controls include the younger and older siblings' skills at the age-3 wave, parental investment, mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, age gap between younger and older sibling, siblings' gender, housing tenure, years lived in current address, region fixed effects.

driven by this sample restriction. Appendix Table A5 replicates Appendix Table A4 using the full sample, including the only-child sample. For children without siblings, the sibling bond variable and the older sibling's socio-emotional skills variable are imputed to the minimum and maximum observed values, respectively. The specification also controls for the number of siblings and includes an indicator equal to 1 for an only child. The estimates in Appendix Table A5 resemble those in Appendix Table A4, likely because the majority of the sample has at least one sibling.

Overall, Figure 2 and Appendix Table A4 document that the sibling bond remains predictive of developmental outcomes even after conditioning on a rich set of home-environment characteristics. Conceptually, the sibling bond should be interpreted as a summary measure of sibling relationship quality, capturing warmth, enjoyment, and low conflict in everyday interactions. It is therefore closer to relational social capital between siblings than to a broad measure of the home environment. Appendix A.3 builds on the evidence presented above by further examining whether the sibling bond is empirically distinct from parental investment, the mother-child relationship, and the children's own socio-emotional skills. I provide three complementary pieces of evidence. First, Appendix Table A6 shows that the sibling bond is only weakly correlated with home-environment measures such as parental investment, mother's mental health, and the mother-child bond. For example, the correlation with the mother-child bond is 0.11. Second, Appendix Figure A4 shows that the sibling bond is not simply capturing the children's socio-emotional skills: some children with poor socio-emotional skills still have strong sibling interactions, while others with strong socio-emotional skills have low-quality sibling interactions. Third, Section 2.4.1 presents an exploratory factor analysis, documenting that the sibling bond and parental investment items load onto distinct latent factors.

I finally discuss a limitation of the MCS dataset which measures the sibling bond only at the age-5 wave, as such measures are not typically collected in large-scale cohort studies. I therefore document that the age-5 sibling bond predicts later sibling interactions in Appendix Table A7. Columns 1-4 of Appendix Table A7 suggest that a strong sibling bond at age 5 predicts that siblings are more likely to talk to each other rather than their parents at age 14 when worried about something. The age-5 sibling bond also seems to affect other relationships later in life, such as having fewer arguments with parents at age 14 (Columns 5-6 of Appendix Table A7).

To further explore the sibling bond, time-use data would also be helpful to understand how siblings spend their time. Unfortunately, the MCS does not contain such data. On the other hand, the Child Development Supplement (CDS) of the Panel Study of Income Dynamics (PSID) in the United States (US) can provide some interesting insights on this as it collects time-use diaries. Dunifon et al. (2017) present two descriptive patterns in the time use of 6- to 12-year-old children with and without siblings in the U.S., using CDS time-use data.[10] First, children with siblings spend about 50% of their time outside of school engaged with siblings, and another 20% with siblings present, meaning that the vast majority of children's discretionary time is spent with their siblings. Second, siblings spend time in *unstructured play* with each other (almost 2

[10] Dunifon et al. (2017) focus on children's discretionary time, defined as time children are not at school, sleeping, or engaged in personal care such as bathing or dressing (~7 hours per weekday and ~12 hours per weekend day).

hours more per week than only children), while they are more likely to do *structured educational* activities with their parents.[11]

2.3 The joint technology of skill formation with siblings

Building on the descriptive evidence presented above, I extend standard models of human capital investment, which typically assume that parents care about their own consumption, C_i, and the development of an *only* child, θ_i (e.g., Attanasio, 2015). The model accounts for parents with *two* children and incorporates sibling interactions alongside parent-child interactions, as outlined in the stylized model in Appendix A.4.

To capture the complexity of skill formation, I define the joint technology for both the younger (Y) and older (O) siblings in family i at time t, taking into account the multi-dimensional nature of skills: internalizing (INT), externalizing (EXT), and cognitive (COG) skills. I explore several specifications, including a translog production function to allow for different degrees of substitutability between inputs in Appendix A.15. However, the data do not reject the Cobb-Douglas specification, which I therefore adopt for the analysis presented below.

$$ln(\theta^S_{Y,it}) = \sum_S \beta_{1S} ln(\theta^S_{Y,it-1}) + \sum_S \beta_{2S} ln(\theta^S_{O,it-1}) + \beta_{3S} ln(SB_{it}) + \beta_{4S} ln(PI_{it}) + \mathbf{X}_{it}\eta_S + v^S_{Y,it} \quad (1)$$

$$ln(\theta^S_{O,it}) = \sum_S \omega_{1S} ln(\theta^S_{Y,it-1}) + \sum_S \omega_{2S} ln(\theta^S_{O,it-1}) + \omega_{3S} ln(SB_{it}) + \omega_{4S} ln(PI_{it}) + \mathbf{X}_{it}\varphi_S + u^S_{O,it} \quad (2)$$

Where t represents the age-5 wave and $(t-1)$ represents the age-3 wave. Skills θ^S_{it} include internalizing (INT), externalizing (EXT), and cognitive (COG) skills, where $S \in \{\text{INT}, \text{EXT}, \text{COG}\}$. PI_{it} and SB_{it} denote parental investment and sibling bond in the joint technology of skill formation.[12] Both are measured from common latent factors constructed from the same underlying questionnaire items across domains; the superscript S allows their elasticities to differ across skill dimensions. As I am considering the joint process of skill formation with siblings, I incorporate the younger and older siblings' internalizing and externalizing skills at time $(t-1)$. I also control for the younger sibling's cognitive skill in the previous period, while I cannot do that for the older sibling as the MCS does not collect data on the older

[11] Unstructured play allows children the freedom to explore and create without predetermined rules or guidelines, and has been shown to foster cognitive, physical and socio-emotional development (Dankiw et al., 2020; Lee et al., 2020).

[12] Various measures of parental investments can be constructed, each capturing different dimensions such as investment in individual children and joint activities. For the purpose of the estimation, a comprehensive measure of parental investment is constructed, encompassing multiple dimensions of the home environment, including quality interactions, parenting style, joint family activities, interactions with extended family, and the mother-child bond. This approach is adopted to avoid the need for multiple exogenous shifters, as discussed in Section 2.5, which would be necessary to identify several dimensions of investment separately.

sibling's cognitive development.[13] X_{it} is a vector of environmental factors that may affect child development. These include the siblings' gender, age gap between the younger and older sibling, number of children in the household, household structure (dual- or single-headed), mother's education, mother's age, mother's mental health, housing tenure, years lived in current address, local employment rate at the local authority where the family lives, region fixed effects. $v^S_{Y,it}$ and $u^S_{O,it}$ are idiosyncratic shocks observed by the parents, but unobserved by the econometrician.

The analysis focuses on eight sets of parameters: β_{1S}, ω_{1S}, β_{2S}, ω_{2S}, β_{3S}, ω_{3S}, β_{4S}, and ω_{4S}. First, the coefficients β_{1S} and ω_{2S} capture the self-productivity and cross-productivity of skills. Second, β_{2S} and ω_{1S} capture how the older sibling's skills affect the younger sibling's skills, and vice versa. Third, β_{3S} and ω_{3S} capture the productivity of the sibling bond for the younger and older siblings for each skill S. Finally, β_{4S} and ω_{4S} capture the productivity of parental investment for the younger and older siblings for each skill S.

There are two caveats to consider, due to data limitations, in the older sibling's production function. First, only two dimensions of socio-emotional skills can be considered as the older sibling was not the target child of the MCS and data were not collected on cognitive skills. This means that the analysis cannot model potential effects of the older sibling's cognitive skill on the younger sibling's skills. Second, since the older sibling is not the target child of the cohort study, data on them are collected at varying ages. To account for this, I include the older sibling's age as a control in the production function.

The structural estimation of equations (1) and (2) presents two main methodological challenges discussed in Sections 2.4 and 2.5 respectively.

2.4 Measurement system

This section describes the measurement system used to map questionnaire responses into the latent constructs of interest – skills, parental investment, and sibling bond. Following the framework of Cunha et al. (2010), the measurement system efficiently links observed responses to latent factors and sets a measurement scale that ensures comparability of the structural estimates across siblings (Agostinelli and Wiswall, 2025; Freyberger, 2021). I first present an Exploratory Factor Analysis (EFA) to identify latent structures and reduce data complexity, followed by a Confirmatory Factor Analysis (CFA) to validate the proposed factor structure.

2.4.1 Exploratory factor analysis

The psychometric literature identifies two dimensions of socio-emotional development: internalizing (ability to focus drive and determination) and externalizing (ability to engage in interpersonal activities) skills (Achenbach, 1966; Achenbach et al., 2016; Goodman, 1997,

[13] Data on cognitive skills are only available for the younger sibling (i.e., the cohort member of the MCS), while data on socio-emotional skills were collected from one randomly-selected older sibling if there is more than one older sibling.

2001; Goodman et al., 2010). The conduct and hyperactivity scales from the SDQ can be employed to obtain a measure of externalizing skill, while the emotional and peer problem scales can be used to obtain a measure of internalizing skill (Goodman, 1997, 2001; Goodman et al., 2010).[14] Similarly, parental investment and the sibling bond can represent two different dimensions of interactions: parent-child and sibling interactions (McHale et al., 2012; Francesconi and Heckman, 2016).

I investigate these divisions empirically in my dataset via an exploratory factor analysis. This enables me to identify which measures are relevant to which factor and test the hypothesis that a dedicated system, where a single factor loads on each of the available measures, represents the data well. Then, using this evidence, I proceed to the estimation of the measurement system I use in the estimation of the joint technology of skill formation (Section 2.6).

First, I investigate the division in internalizing and externalizing skills and confirm it in my dataset with an exploratory factor analysis. I estimate the factor loadings from the exploratory factor analysis, based on decomposing the polychoric correlation matrix of the items and using maximum likelihood estimation (Olsson, 1979).[15] The exploratory factor analysis of the SDQ shows a clear separation between items and supports the division in internalizing and externalizing skills proposed by theory (Appendix Table A8). The factor loadings also have similar magnitudes across siblings, highlighting the similar association between the items and the factors across the younger and older siblings.

Second, I perform an exploratory factor analysis to verify whether parental investment and the sibling bond capture a single latent factor, namely the "home environment" (see also Section 2.2). The exploratory factor analysis in Table 1 supports the existence of two distinct latent factors and shows a clear separation between items. The questionnaire items related to parental investment are highly correlated with the first latent factor (parental investment) and the items related to the sibling bond are highly correlated with the second latent factor (sibling bond). Another takeaway from the table is that item assignment to the latent constructs is data-driven and follows directly from the estimated factor loading structure, rather than from interpretative priors, such as assuming ex ante that less sibling fighting reflects a stronger bond. Finally, Appendix Table A9 reproduces Table 1 using the questionnaire items residualized by the set of controls previously described. The results are even more pronounced: the correlation between the two latent factors decreases from 0.15 to 0.06 after residualization.

As a robustness check, I also perform an exploratory factor analysis of the questions meant to measure (i) parental investment, (ii) sibling bond, (iii) younger sibling's internalizing and (iv) externalizing skills at age 5. This robustness check investigates if the questionnaires are capturing four different latent constructs. Reassuringly, Appendix Table A10 shows that questionnaire items meant to measure a certain latent factor load on that specific latent factor,

[14] Goodman et al. (2010) suggest using these two dimensions of socio-emotional development in low-risk samples, such as the MCS, while using the five separate SDQ subscales in high-risk children.

[15] The polychoric correlation estimates the correlation between two standard normal latent factors underlying ordinal responses.

Table 1: Exploratory factor analysis of the sibling bond and parental investment questions

Item	Parental investment	Sibling bond
Younger sib likes to be with older sib	-0.048	**0.872**
Younger sib interested in older sib	-0.061	**0.657**
Younger sib has fun with older sib	-0.003	**0.832**
Younger sib does not tease older sib	-0.016	**0.355**
How often do you read to child	**0.415**	0.027
How often tells stories to child	**0.501**	-0.041
How often does musical activities with child	**0.527**	-0.022
How often does child paint/draw at home	**0.612**	-0.054
How often do you play physically active games with child?	**0.529**	0.055
Frequency play indoor games with child	**0.644**	-0.051
Frequency take child to park or playground	**0.379**	-0.065
How often family does indoor activities together	**0.335**	0.029
How often child sees grandparents	**0.071**	-0.049
How often child sees other relatives	**0.136**	-0.130
How often child spends time with friends outside school	**0.194**	-0.002
How often ignores child when naughty	**-0.049**	0.066
How often smacks child when naughty	**-0.195**	-0.054
How often shouts at child when naughty	**0.178**	0.142
How often sends child to bedroom/naughty chair	**-0.028**	0.098
How often takes away treats from child when naughty	**-0.009**	0.084
How often tells child off when naughty	**0.161**	0.108
How often bribes child when naughty	**-0.048**	-0.008
How often tries to reason with child when naughty	**0.025**	-0.046
How often makes sure child obeys instruction/request	**0.092**	0.158
How close bond between mother and child	**0.243**	0.186

Note. The table displays the factor loadings obtained from exploratory factor analysis (EFA) of the sibling bond and parental investment questions. The EFA is based on the decomposition of the correlation matrix. The solution is rescaled using oblique factor rotation obtained via the PROMAX protocol (with $k = 3$). I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling).

while being uncorrelated with the other factors.

Finally, Appendix Table A11 reports Cronbach's alphas, which are usually above 0.53 for all the latent factors considered. Cronbach's alpha is a measure of internal consistency used to assess scale reliability, indicating how closely related a set of items are within each latent factor (Cronbach, 1951). It ranges from 0 to 1, with values closer to 1 indicating higher reliability; values above 0.50 are generally considered acceptable (Taber, 2018).

2.4.2 Confirmatory factor analysis

This section presents the measurement system based on categorical items that allows for a careful treatment of the multi-dimensionality of skills and enables the analysis of two distinct dimensions of socio-emotional development. Relative to earlier studies using continuous items and fewer dimensions of skills, this framework provides greater flexibility in representing latent skill heterogeneity.

The categorical response, m_{cijt}, to the questionnaire item j for child c (i.e., the younger or the older sibling) in family i at time t is assumed to be a manifestation of a latent item m^*_{cijt}, which in turn depends linearly on the logarithm of the latent factors $ln\theta_{cit}$ by item-specific intercepts

α_{jt} and loadings λ_{jt} and an independent measurement error term ε_{cijt}. For ease of notation, I omit the subscripts c in the factor model for the younger and older sibling in equations (3) and (4).

$$m^*_{ijt} = \alpha_{jt} + \lambda^{\top}_{jt} ln\theta_{it} + \varepsilon_{ijt} \tag{3}$$

Specifically, m^*_{ijt} maps into m_{ijt} via a threshold model:

$$m_{ijt} = \begin{cases} 0 & \text{if } m^*_{ijt} < \tau_{1,jt} \\ 1 & \text{if } m^*_{ijt} \in \left[\tau_{1,jt}, \tau_{2,jt}\right] \\ 2 & \text{if } m^*_{ijt} > \tau_{2,jt} \end{cases} \tag{4}$$

Where τ_{jt} is the threshold, for example, for showing a certain behavior in the SDQ scale or an interaction in the sibling bond scale. I consider a dedicated factor structure, where each item loads only on one latent dimension, following the structure found in the exploratory factor analysis in Section 2.4.1 (Heckman et al., 2013). Latent factors and the measurement error terms are normally distributed: $ln\theta_{it} \sim \mathcal{N}\left(\mu_{\theta,t}, \sigma_{\theta,t}\right)$ and $\varepsilon_{ijt} \sim \mathcal{N}\left(0, \sigma_{\varepsilon,jt}\right)$. Some normalizations are also needed in equations (3) and (4) for the parameters to be identified. First, the intercepts and the thresholds cannot be jointly identified in a factor model with categorical items. Intercepts are assumed zero, $\alpha_{jt} = 0, \forall j, t$. Second, to let the mean and the variance of the latent factor be estimated, I normalize $\lambda_{jt} = 1$ and $\tau_{1,jt} = 0$ at the age-3 and age-5 waves for the younger and older siblings, respectively, on the following SDQ items: (i) *"Often complaining of headaches, stomach-aches or sickness"* to measure the internalizing skill, and (ii) *"Has often had temper tantrums or hot tempers"* to measure the externalizing skill.

Additionally, Appendix A.6 draws on advances in psychometrics to present a test for measurement invariance (Vandenberg and Lance, 2000; Putnick and Bornstein, 2016; Wu and Estabrook, 2016). This test assesses whether assuming a common metric for the latent socio-emotional skills of younger and older siblings is appropriate. By establishing measurement invariance, the analysis strengthens the construct validity of comparisons of the structural estimates of the skill formation technology between younger and older siblings.

To measure cognitive skills, I use a factor model with continuous items (Appendix A.7). I set the constant α_{jt} to 0 and the loading λ_{jt} to 1 for the "naming vocabulary test", which has been administered at the age-3 and age-5 waves for the younger sibling, and let the mean and the variance of the latent factor be estimated (Agostinelli and Wiswall, 2025).

To measure the latent factors capturing parental investment and the sibling bond, I use the factor model outlined in this section and set the mean to 0 and the standard deviation to 1 for the identification of each latent factor. This normalization specifies the underlying assumptions for the comparison of the productivity of these inputs.

2.5 Investment functions

A second challenge in estimating the technology of skill formation is that inputs are likely to be correlated with unobserved shocks to child development (Todd and Wolpin, 2003; Cunha, Heckman, and Schennach, 2010; Attanasio, Cattan, Fitzsimons, Meghir, and Rubio-Codina, 2020; Attanasio, Meghir, and Nix, 2020).[16] Parents and siblings may adjust their actions, depending on developmental shocks to human capital, making the inputs endogenous. For example, parents may adjust their investment at time t in response to unobserved shocks that affect their choices as well as the level of development. Similarly, siblings experiencing a positive shock to socio-emotional skills, unobserved by the econometrician, may be more likely to have positive interactions and fewer conflicts with their siblings. Ignoring this endogeneity would provide biased estimates of the productivity of parental investment and the sibling bond.

Ideally, to address this problem, I would need random assignment of parental investment and the sibling bond to the child, but of course this is not always feasible. A feasible alternative is to use some exogenous shifters for parental investment and the sibling bond, motivated by the theoretical model in Appendix A.4, which derives the economic restriction consistent with the exogeneity condition. This approach follows the literature which has adopted a similar strategy to deal with the endogeneity of parental investment when estimating the technology of skill formation for only-child households. Some examples of exogenous shifters for parental investment are: innovations in income (Cunha, Heckman, and Schennach, 2010), variation in prices (Attanasio, Meghir, and Nix, 2020), and variation in prices and exposure to conflicts (Attanasio, Cattan, Fitzsimons, Meghir, and Rubio-Codina, 2020).

In all these cases, a theoretical framework helps derive *sufficient* conditions under which the exogenous shifters are valid and consistent with economic theory. However, these conditions are only sufficient, since the model cannot capture every possible household response to unobserved shocks. Cunha et al. (2021) argue that the *necessary* conditions for the exogenous shifters to be valid depend on the nature of the unobserved shocks. For example, if the unobserved shocks capture transitory or low-adjustment-cost omitted inputs, then the exclusion restriction would be difficult to satisfy as unobserved inputs could change in response. On the other hand, if the omitted inputs can only change at significant cost, such as moving to a different neighborhood, then the exogenous shifters would satisfy the exclusion restriction.

In principle, the investment functions could be computed numerically by solving the dynamic problem faced by parents, as in Del Boca et al. (2014) and Gayle et al. (2015). Doing so, however, would require stronger assumptions about parental behavior, including that parents have full knowledge of the production function. This assumption conflicts with evidence showing that parents in both developed and developing countries hold biased beliefs about the returns to investment in children (Cunha et al., 2013; Boneva and Rauh, 2018; Attanasio et al., 2019). Instead, I approximate the investment functions directly, following (Attanasio, Meghir, and Nix,

[16] A similar problem is faced in industrial organization when estimating production functions (see for example, Olley and Pakes (1996)).

2020; Attanasio, Cattan, Fitzsimons, Meghir, and Rubio-Codina, 2020), which avoids taking a stance on whether parents know the true production function. I therefore use log-linear investment functions derived from the parental investment model in Appendix A.4.

$$ln(SB_{it}) = \sum_{S} \delta_{1S} ln(\theta^{S}_{Y,it-1}) + \sum_{S} \delta_{2S} ln(\theta^{S}_{O,it-1}) + \delta_3 Z_{1,it} + \delta_4 Z_{2,it-1} + \mathbf{X}'_{it}\phi_S + \epsilon^{SB}_{it} \quad (5)$$

$$ln(PI_{it}) = \sum_{S} \gamma_{1S} ln(\theta^{S}_{Y,it-1}) + \sum_{S} \gamma_{2S} ln(\theta^{S}_{O,it-1}) + \gamma_3 Z_{1,it} + \gamma_4 Z_{2,it-1} + \mathbf{X}'_{it}\phi_I + \epsilon^{PI}_{it} \quad (6)$$

The investment functions in equations (5) and (6) depend on the younger and older siblings' skills at time $t-1$, parental background, and a set of household characteristics captured by $\mathbf{X}_{it}$. To address the potential endogeneity and simultaneity between parental investment and sibling bond, the two inputs are modeled as jointly determined endogenous variables within a structural system of simultaneous equations. This approach identifies their respective impacts through the use of exclusion restrictions and appropriate instruments, $Z_{i,1t}$ and $Z_{2,it-1}$, mitigating bias in the estimation of the skill production functions. These instruments are assumed to affect children's skill development only indirectly – through their influence on one of the endogenous variables – without entering the production function of skills directly. I discuss the identification strategy, the choice of instruments, and their limitations in detail in the following paragraphs.

To address the endogeneity of parental investment, I use a local female employment shock, $Z_{i,1t}$, proxied by the local female employment rate at the local authority level where the household resides at the age-5 wave, using geocoded data. The richness of the MCS helps support the assumption that variation in this shock is more plausibly exogenous because I can condition on a large set of controls, $\mathbf{X}_{it}$, such as local employment rate in the local authority, partner being present in the household and many other variables capturing household resources. The identifying assumption is that, conditional on controls, variation in the local female employment rate affects child development only through parental investment (Carneiro et al., 2013). The female employment shock is a relevant shifter because it could affect the household's labor supply, in turn affecting the amount of parental investment.

To address the endogeneity of sibling bond, I use a housing-based shifter, $Z_{2,i,t-1}$, proxied by the number of rooms in the household at the age-3 wave, excluding bathrooms, toilets, halls, and garages. The identifying assumption is that, conditional on the rich set of controls X_{it}, variation in room count affects age-5 skill formation only through sibling bond. A concern is that housing space may also affect child development directly, for example through sleep quality, privacy, or study conditions. I cannot test this exclusion restriction directly. I therefore assess its plausibility in Section 3.1 using balance checks, placebo evidence, and the fact that room count predicts sibling bond but not parental investment conditional on observables. The housing-based shifter is relevant because variation in household space may affect the frequency and quality of sibling interactions, in turn affecting the strength of the sibling bond. I discuss the relevance and monotonicity of the exogenous shifters in Section 3.1.

2.6 Estimation

The factor model, the production function and the investment functions are estimated in one step. A more intuitive procedure would follow two steps. In a first step, the factor model is estimated and the factors are predicted. Then in the second step, the factor scores predicted in the previous step are used to estimate the production function. This method is, however, not recommended as the first step involves measurement error from the prediction, which could lead to attenuation bias in the second step (Cunha et al., 2021).

The one-step estimation strategy was developed in the psychometric literature by Muthén (1983, 1984) and has also been adopted by Attanasio, de Paula, and Toppeta (2025). This approach relies on the generalized method of moments (GMM), which makes it more computationally tractable to estimate measurement systems with *categorical* items. Alternative approaches have been used in the literature for factor models with *continuous* items.[17]

I outline the estimation methodology below. The strategy estimates the parameters of the measurement system, the skill formation technology, and the investment process using GMM. The moments for the factor model are constructed from the polychoric correlations among the categorical items m_{ijt}, while the remaining moments are implied by the production and investment equations.

Following the terminology in Muthén (1984), the model distinguishes between "reduced-form" and "structural" parameters. The reduced-form parameters include thresholds, slopes, and covariance terms, all of which are functions of the structural parameters governing the factor model and the system of regressions of interest. Letting ρ denote the reduced-form parameters and β the structural parameters, one can write $\rho = g(\beta)$, for a known function $g(\cdot)$.

For simplicity, let $\theta \in \mathbb{R}$ denote child skill, and let $S = \begin{bmatrix} SB \\ PI \end{bmatrix} \in \mathbb{R}^2$ collect the sibling bond (SB) and parental investment (PI). Let $\mathbf{X}$ and $\mathbf{Z}$ denote vectors of observed covariates. Omitting i subscripts, the latent system can be written compactly as

$$\underbrace{\begin{bmatrix} \theta \\ S \end{bmatrix}}_{:=\eta} = \underbrace{\begin{bmatrix} \phi \\ \pi_0 \end{bmatrix}}_{:=A} + \underbrace{\begin{bmatrix} 0 & \gamma^\top \\ 0 & 0 \end{bmatrix}}_{:=B} \begin{bmatrix} \theta \\ S \end{bmatrix} + \underbrace{\begin{bmatrix} \omega^\top & 0 \\ \pi_X & \pi_Z \end{bmatrix}}_{:=\Gamma} \begin{bmatrix} \mathbf{X} \\ \mathbf{Z} \end{bmatrix} + \underbrace{\begin{bmatrix} \nu \\ \epsilon \end{bmatrix}}_{:=\xi},$$

where the first row represents the skill production function and the remaining rows represent the

[17]These include a non-linear filtering method (Cunha et al., 2010), a three-step simulation algorithm (Attanasio et al., 2020), the generalized method of moments (Agostinelli and Wiswall, 2025), and a bias-correction method for two-step estimation (Croon, 2002; Heckman et al., 2013). Appendix A.7 describes factor models with continuous and categorical items.

equations determining the components of S. This follows the setup in equation (3) in Muthén (1984). Using the notation in that reference, the system can be rewritten as

$$\eta = (I - B)^{-1}A + (I - B)^{-1}\Gamma \begin{bmatrix} \mathbf{X} \\ \mathbf{Z} \end{bmatrix} + (I - B)^{-1}\xi.$$

Using the measurement equation for categorical items (see Section 2.4.2),

$$m_j^* = \alpha_j + \lambda_j^\top \eta + \varepsilon_j,$$

it follows that

$$m_j^* = \alpha_j + \lambda_j^\top (I - B)^{-1}A + \lambda_j^\top (I - B)^{-1}\Gamma \begin{bmatrix} \mathbf{X} \\ \mathbf{Z} \end{bmatrix} + \lambda_j^\top (I - B)^{-1}\xi + \varepsilon_j.$$

Under the assumption that the composite error term $\lambda_j^\top (I-B)^{-1}\xi + \varepsilon_j$ is normally distributed, the latent responses m_j^* are multivariate normal conditional on the observed covariates. In this setting, the vector $\hat{\rho}$ collects the reduced-form parameters of the model, including item thresholds, the polychoric correlations among the questionnaire items, and the coefficients from the reduced-form regressions of m_j^* on the observed covariates. These reduced-form parameters are deterministic functions of the structural parameters β governing the measurement system, the skill formation technology, and the equations for sibling bond and parental investment, as summarized by the mapping $\rho = g(\beta)$.

Once the estimates $\hat{\rho}$ are obtained, the structural parameters are estimated using a minimum-distance estimator based on the objective function

$$F_W(\beta) = (g(\beta) - \hat{\rho})^\top \mathbf{W}^{-1} (g(\beta) - \hat{\rho}), \tag{7}$$

where $\mathbf{W}$ is a weight matrix and the minimization is carried out with respect to β. Muthén (1978) recommends using a consistent estimator of the asymptotic covariance matrix of $\hat{\rho}$ as the weight matrix $\mathbf{W}$. The resulting estimator of β is known in the psychometrics literature as the Weighted Least Squares (WLS) estimator. In this analysis, I use the Diagonally Weighted Least Squares (DWLS) estimator, which relies only on the diagonal elements of $\mathbf{W}$ and offers computational advantages as well as improved performance in small samples (Muthén, 1997).

3 Structural estimates

This section presents the structural estimates of the investment and production functions for externalizing, internalizing, and cognitive skills for the younger and older siblings during childhood, as well as illustrative counterfactual simulations based on the estimated model. The structural framework allows me to quantify the channels through which family interactions shape skill formation, including self-productivity, cross-sibling effects, and the productivity of parental investment and the sibling bond. The younger sibling's skills (i.e., those of the cohort member) are measured at age 5 for every child, while the older sibling's skills are measured at different ages. I therefore control for the older sibling's age in the production function. The factor model, the production function, and the investment function are estimated in one step. The coefficients in the tables are elasticities, as all variables are in logs except for the dummies and categorical variables.

3.1 Investment function estimates

The estimates of the investment functions are presented in Table 2, where Column 1 focuses on the sibling bond and Column 2 on parental investment. Studying the determinants of these two inputs is relevant for understanding the origin of disadvantage and, in turn, understanding how to intervene to break its intergenerational transmission.

Table 2: Investment functions: Sibling bond and parental investment

Outcome	**Sibling bond** (1)	**Parental investment** (2)
Number of rooms (t-1)	0.066***	0.011
	(0.017)	(0.012)
Local female employment rate	-0.019	0.046***
	(0.013)	(0.009)
Younger sib's EXT skill (t-1)	0.180***	0.190***
	(0.032)	(0.024)
Younger sib's INT skill (t-1)	0.039	0.304***
	(0.089)	(0.070)
Younger sib's COG skill (t-1)	0.061**	-0.032
	(0.029)	(0.021)
Older sib's EXT skill (t-1)	0.304***	0.119***
	(0.028)	(0.019)
Older sib's INT skill (t-1)	0.136**	-0.048
	(0.058)	(0.043)
Test of joint significance: F-statistic (p-value)		
Number of rooms (t-1)	14.867 (0.000)	
Local female employment rate		25.211 (0.000)
Observations	2558	2558
Other controls	Yes	Yes

Note. The table presents the structural estimates of the investment functions. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, housing tenure, years lived in current address, local employment rate in the local authority where family lives, region fixed effects. The questionnaire items used to measure the latent sibling bond and parental investment are presented in Table 1. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Column 1 presents the estimates of the determinants of the sibling bond. The younger and older siblings' externalizing skills, not surprisingly, are important determinants of the sibling bond. Children with a higher ability to engage in interpersonal activities at time $(t-1)$ are more likely to enjoy a stronger bond at time t. Turning attention to the exogenous shifter, the number of rooms at $(t-1)$ is positively and significantly associated with the sibling bond, as shown by the F-statistic and p-values (Column 1 of Table 2). The positive first-stage association is consistent with the idea that household space shapes the frequency and quality of sibling interactions.

I acknowledge the limitations of using the number of rooms as an exogenous shifter for sibling bond. The main threat to identification is that the number of rooms may affect children's skill development directly, rather than only through sibling bond. For example, larger homes may improve sleep quality, study conditions, privacy, or opportunities for solitary activities independently of sibling interaction. This exclusion restriction cannot be tested directly. I therefore provide four pieces of indirect evidence that make the identifying interpretation more plausible, using the rich background information in the MCS to condition on detailed family and household characteristics, following previous work that instruments endogenous family investments (Cunha, Heckman, and Schennach, 2010; Attanasio, Cattan, Fitzsimons, Meghir, and Rubio-Codina, 2020; Attanasio, Meghir, and Nix, 2020).

First, the instrument is measured at age 3, prior to the age-5 skill outcomes. In addition, the MCS allows me to compare households with similar family composition and similar housing characteristics – including housing tenure, residential stability, and regional location – where siblings may share a bedroom in some households but not in others. Importantly, the room measure excludes bathrooms, toilets, halls, and garages, so the relevant variation captures usable living space relevant for how closely siblings live with one another inside the home rather than broader housing amenities. Second, conditional on the full set of controls, room count predicts sibling bond but not parental investment. This asymmetric first-stage pattern is more consistent with a mechanism operating through within-home sibling interaction conditions than with one operating through broad household advantage. If room count mainly captured overall housing quality rather than space allocation between siblings, one might expect it to predict parental investment as strongly as sibling bond. Table 2 does not support this pattern: the coefficient in the parental investment equation is small and statistically insignificant (Column 2: coefficient 0.011, $p > 0.10$). Third, Appendix Table A13 presents a balance check showing that, conditional on controls, the shifter is not systematically related to predetermined characteristics. Fourth, Appendix Table A14 conducts a placebo exercise in the only-child sample, where sibling bond is absent by construction. Although the number of rooms is correlated with child outcomes in uncontrolled specifications, these associations become small and statistically insignificant once the baseline controls are included. Taken together, these results provide supportive, though not definitive, evidence for the identifying interpretation. Nevertheless, convincingly testing the exogeneity condition remains challenging.

Column 2 presents the estimates of the determinants of parental investment. The exogenous shifter is the local female employment rate in the local authority where the household lives (Carneiro et al., 2013). The local female employment rate is a relevant shifter as reported by the F-statistics and p-values in Table 2. The positive association between the local female employment rate and parental investment suggests that, despite potential time constraints due to work commitments, the increased resources from employment allow for a higher level of parental investment in terms of quality interactions with the children (Leibowitz, 1974; Guryan et al., 2008).

The identifying assumption is that variation in the local female employment rate affects children's skills primarily through parental investment. First, in support of this, the local female employment rate appears to affect skill formation only through parental investment (Column 2 of Table 2), but not through the sibling bond (Column 1). Second, the extensive set of controls includes factors, such as local employment rate in the local authority where the family lives, which can account for additional influences on the outcomes of interest. By incorporating them, I can more accurately examine the specific effects of the variables under investigation, while mitigating the potential confounding effects of other factors. Third, Appendix Table A13 shows balance across pre-determined characteristics for the exogenous shifters when the rich set of controls is included.

Before turning to the production function estimates, it is important to discuss the monotonicity of the exogenous shifters. Appendix Tables A15-A18 reproduce Table 2 for different sub-samples defined by: younger sibling's gender, older sibling's gender, siblings' gender composition and siblings' age gap. Appendix Tables A15-A18 show that the coefficients on the number of rooms at time $t-1$ and the local female employment rate do not change sign and have a similar magnitude across subgroups, providing support for their monotonicity.

3.2 Production function estimates

This section discusses the estimates of the joint technology of skill formation for the younger and older siblings when treating investments as endogenous (Table 3). Outputs are externalizing, internalizing and cognitive skills. Studying these different dimensions of skills provides insights into the complexity of the development process and the interplay between each skill dimension. Columns 1-4 of Table 3 present the estimates for the externalizing skill, Columns 5-8 for the internalizing skill, and Columns 9-10 for the cognitive skill. Even Columns present the estimates, when considering siblings and allowing the sibling bond to be productive, while Odd Columns present the estimates of the skill formation technology, when assuming an only child and restricting the sibling bond to have a productivity of zero (Cunha and Heckman, 2008; Cunha, Heckman, and Schennach, 2010; Attanasio, Cattan, Fitzsimons, Meghir, and Rubio-Codina, 2020; Attanasio, Meghir, and Nix, 2020; Agostinelli and Wiswall, 2025). Appendix Table A19 reports the estimates of the joint technology when investments are treated as exogenous.

There are two general considerations to highlight before turning to the productivity of the sibling bond and parental investment. First, skills are self-productive (Cunha et al., 2010). This holds true for each skill dimension and sibling. For example, a 10% increase in the externalizing skill at time $t-1$ translates into a 5.0% and 5.95% increase respectively in the younger and older siblings' externalizing skill at time t (Columns 2 and 4). The more persistent dimension of development is the internalizing skill, where a 10% increase in the internalizing skill at time $t-1$ translates into a 7.5% and 9.4% increase respectively in the younger and older siblings'

Table 3: Joint technology of skill formation: younger and older siblings

Outcome	Externalizing (EXT)				Internalizing (INT)				Cognitive (COG)	
	Younger		Older		Younger		Older		Younger	
	Restricted	Unrestricted	Restricted	Unrestricted	Restricted	Unrestricted	Restricted	Unrestricted	Restricted	Unrestricted
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Younger sib's EXT skill (t-1)	0.569***	0.500***		-0.277***	-0.050*	-0.107**		-0.099*	0.005	-0.068
	(0.060)	(0.076)		(0.071)	(0.028)	(0.047)		(0.053)	(0.047)	(0.068)
Younger sib's INT skill (t-1)	-0.338***	-0.282***		-0.260**	0.769***	0.750***		-0.313***	-0.204*	-0.127
	(0.094)	(0.091)		(0.109)	(0.108)	(0.108)		(0.093)	(0.106)	(0.109)
Younger sib's COG skill (t-1)	0.113***	0.089***		0.038	-0.015	-0.038*		0.046*	0.598***	0.568***
	(0.022)	(0.027)		(0.029)	(0.015)	(0.022)		(0.026)	(0.030)	(0.035)
Older sib's EXT skill (t-1)		-0.176**	0.680***	0.595***		-0.166***	-0.142***	-0.219***		-0.172**
		(0.065)	(0.043)	(0.078)		(0.051)	(0.027)	(0.060)		(0.075)
Older sib's INT skill (t-1)		0.000	-0.077*	-0.007		-0.015	0.868***	0.943***		-0.093
		(0.047)	(0.041)	(0.055)		(0.039)	(0.078)	(0.088)		(0.059)
Parental investment (t)	0.559***	0.460**	0.662***	0.624***	0.212*	0.194	0.167	0.225	0.432**	0.331
	(0.184)	(0.196)	(0.195)	(0.281)	(0.115)	(0.150)	(0.128)	(0.159)	(0.211)	(0.242)
Sibling bond (t)		0.406**		0.397**		0.344**		0.242*		0.491**
		(0.172)		(0.195)		(0.133)		(0.145)		(0.200)
Observations	2558	2558	2475	2475	2558	2558	2475	2475	2558	2558
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note. The table presents the structural estimates of the joint technology of skill formation. Younger sibling at age 5, older sibling between age 6 and 15. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual- or single-headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. The questionnaire items used to measure the latent sibling bond and parental investment are presented in Table 1. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

internalizing skill at time t (Columns 6 and 8).[18]

Second, siblings' socio-emotional skills also matter. Cunha et al. (2010), Attanasio et al. (2020), Attanasio, Meghir, and Nix (2020), and Agostinelli and Wiswall (2025) abstract from this channel because they are formulated within an only-child framework. I show that an increase in the older (younger) sibling's externalizing skill at $t-1$ is negatively associated with the younger (older) sibling's skills. For example, a 10% increase in the older sibling's externalizing skill at time $t-1$ translates into a 1.8% decrease in the younger sibling's externalizing skill at time t (Column 2). One possible interpretation is that the older sibling's externalizing skill spills over to the younger sibling, but this would require additional assumptions – most importantly, that influence runs only from the older to the younger sibling and that timing rules out simultaneous determination (Altonji et al., 2017).[19] Unfortunately, I cannot control for the endogeneity of such spillover (Manski, 1993). Finding another exogenous shifter for the siblings' socio-emotional skills within the family is quite demanding. This finding calls for additional research, as a negative spillover could have implications for policies aimed at improving only one sibling's interpersonal skills.[20]

Turning to the sibling bond and parental investment, Table 3 documents that the sibling bond enters the production function as a productive input, alongside parent-child interactions, in the

[18] It would be interesting to consider additional lags of skills as done in Attanasio et al. (2020) and Attanasio et al. (2020) who study how persistent the development process is, questioning whether it follows a first-order Markov chain. Unfortunately, this is not possible in my setting due to data limitation as the $t-2$ wave is at birth.

[19] The influence from the older to younger sibling is, however, supported by several studies in psychology as a first approximation (Buhrmester et al., 1992; Rodgers and Rowe, 1988).

[20] The psychology literature has theorized that if one sibling has a high externalizing skill, then the other one is likely to have a high internalizing skill and vice versa (Plomin and Daniels, 1987). This could, for example, be because a sibling with a strong externalizing skill, which corresponds to a high ability to engage in interpersonal activity, might overshadow the other sibling and push her/him to develop another dimension of skill where s/he could have a comparative advantage.

younger and older siblings' joint technology of skill formation.[21] The comparison between Odd and Even Columns further suggests that part of the effect of parent-child interactions may operate through sibling interactions, which are more likely when siblings are more closely connected, that is, when they share a stronger sibling bond. For example, a 10% increase in the sibling bond at time t translates into a 4.06% and 3.97% increase respectively in the younger and older siblings' externalizing skill at time t (Columns 2 and 4). This result also complements the literature on the trade-off between quantity and quality of children (Becker and Lewis, 1973; Willis, 1973; Becker and Tomes, 1976), suggesting that interventions aimed at encouraging prosocial behavior and constructively mediating sibling conflict, rather than only reinforcing or compensating for sibling inequality, may foster the skills of both siblings.

In addition, Appendix Figure A5 illustrates graphically the quantitative importance of the sibling bond and parental investment by presenting their marginal productivity across age-3 skill levels.[22] This figure is useful to reiterate two points. First, there is complementarity between the age-5 input and age-3 skill for each skill dimension, reinforcing that differences in the sibling bond may be associated with persistent inequalities across households. Indeed, high-SES children are more likely to have both higher initial skills and a stronger sibling bond (Section 2.2), and would also benefit from a higher estimated productivity of the sibling bond (Appendix Figure A5). Second, the figure summarizes the relative marginal productivity of parental investment and the sibling bond within the estimated joint technology of skill formation, with a larger gap appearing for internalizing skills.

Robustness checks: Table 3 uses the data on the sibling bond between the cohort member (i.e., younger sibling) and the randomly-selected older sibling whose data on socio-emotional skills have been collected by MCS. This allows me to condition on the younger and older siblings' socio-emotional skills and capture the productivity of the sibling bond conditional, for example, on their ability to engage in interpersonal activities and focus their determination. Appendices A.13 and A.14 present evidence that the estimates of the sibling bond productivity in Table 3 are robust to using the average sibling bond in families with at least two older siblings and to family size. First, Appendix Table A20 reproduces Table 3 by using the average of the sibling bonds from each sibling combination when the younger sibling has at least two older siblings, and finds similar estimates for the productivity of the sibling bond (about 50% of children have at least two siblings). Second, Appendix Table A21 reproduces the estimates for Table 3, instrumenting family size with the siblings' gender composition, and provides suggestive evidence that the estimates are robust. It is important to highlight that the exogenous shifter for family size (i.e.,

[21] Similar evidence also emerges when investments are treated as exogenous (Appendix Table A19).

[22] The marginal productivity of parental investment (sibling bond) is constructed using the estimates of the production function, evaluated at each percentile of the age-3 skill, while holding the sibling bond (parental investment) at the age-3 skill-percentile-specific mean and the other inputs at the median in the sample. The marginal productivity of the input is expressed in standard deviation units, corresponding to a one-standard-deviation increase in the input.

siblings' gender composition) is weak; estimates must therefore be taken with caution.

The estimates presented in Table 3 assume a Cobb-Douglas specification. Appendix A.15 experiments with different functional form assumptions for the production function, such as a translog production function, where the elasticity of substitution between inputs can be different from 1. The translog specification investigates whether interactions between the sibling bond and lagged sibling skills, and between the sibling bond and parental investment, affect skill formation. The estimates for the translog production function are presented in Appendix Table A22. The restrictions implied by the Cobb-Douglas specification do not seem to be rejected, suggesting that the Cobb-Douglas specification constitutes a good approximation in my dataset. This is consistent with Attanasio, Cattan, Fitzsimons, Meghir, and Rubio-Codina (2020) and Attanasio, Meghir, and Nix (2020).

Finally, Appendix A.16 exploits measures of the younger sibling's socio-emotional skills, reported by teachers rather than parents, to address concerns related to correlated measurement error arising from a common reporter. Appendix Table A23 reports the estimates of the production function using items from the teachers' socio-emotional questionnaire, yielding structural parameters that are quantitatively similar to the baseline estimates.[23] In contrast, the estimation of the cognitive skill production function is not subject to this concern, as responses to the cognitive tests are collected directly by the MCS interviewers.

Heterogeneity: Appendix A.17 explores two possible sources of heterogeneity in the structural estimates of the siblings' skill formation technology: the siblings' gender and age (Appendix Tables A24-A27). Appendix Table A26 provides some suggestive evidence that the sibling bond could be more productive for same-sex than mixed-sex siblings. On the other hand, Appendix Table A27 suggests that the effect of sibling bond varies by siblings' age gap. Closer age gaps could encourage shared activities and mutual learning, enhancing cognitive skills, while larger age gaps could allow the older sibling to act as a role model, promoting socio-emotional skills. Unfortunately, the structural estimates become imprecise as the exogenous shifters become weak when the sample is split and investments are allowed to be endogenous (Appendix Tables A15-A18).

Validating the structural estimates: I perform a validation exercise to check how well the model does in terms of out-of-sample prediction. I use the structural estimates of the younger sibling's skill formation technology at age 5 in Table 3 to simulate their skills over the life-cycle at ages 5, 7, 11, 14 and 17, iterating the model for each younger sibling i, based on the baseline inputs and skills. Appendix Figure A6 presents the binscatter plot of the realized skills against the simulated skills from the structural model, showing that the model performs well in

[23] This analysis allows me to measure the latent externalizing skill at age 5 using similarly-worded items across parent and teacher questionnaires, differing only by the identity of the respondent. Appendix A.16 presents the similarly-worded items across questionnaires.

terms of the out-of-sample prediction across adolescence. This analysis builds confidence in the counterfactual simulations presented next.

Using the structural estimates: I use the estimated model to conduct illustrative counterfactual simulations. These exercises are not policy evaluations. Rather, they show how the estimated production function maps changes in parental investment or sibling bond into later skills under the maintained assumptions of the model. These simulations may be informative about policy-relevant mechanisms, such as interventions that facilitate positive sibling interactions, mediate sibling conflict, or reduce crowding and increase privacy within the home.[24] They should not, however, be interpreted as estimates of the effects of such policies. As highlighted in Appendix A.4, the model suggests that family interactions may operate jointly through both parents and siblings.

Appendix Figure A7 presents counterfactual simulations that illustrate how the estimated production function maps changes in either the sibling bond or parental investment into subsequent skills. I simulate a persistent one-standard-deviation increase in only the sibling bond and, separately, in only parental investment over periods 1 to 5 (ages 5, 7, 11, 14, and 17), while fixing all other inputs at their sample median values and assuming that the production function parameters remain constant across simulated periods. Holding the parameters of the production function fixed at different developmental stages is a strong assumption, but finds some support in this context by the validation exercise presented above (see also Appendix Figure A6). Under these maintained assumptions, the simulations suggest that the largest dynamic responses are observed for socio-emotional skills.

4 Conclusion

Understanding the technology of skill formation is an important topic in labor economics. The literature has studied skill formation within an *only*-child framework, establishing that parent-child interactions and parental skills are important determinants of human capital formation during childhood. By contrast, the role of siblings in skill formation has received much less attention, even though the majority of children in most countries have at least one sibling. As siblings grow up together, they interact daily and may form bonds that outlast many other family relationships. A strong sibling bond may facilitate cooperation, social support, and role-model effects within the family.

This paper formalizes and estimates a structural model of the joint technology of skill formation for younger and older siblings. The Millennium Cohort Study in the United Kingdom

[24] So far, policies have mostly focused on stimulating parent-child interactions while paying limited attention to siblings (e.g., Evans et al. (2021)). Leijten et al. (2021) review randomized controlled trials designed to improve sibling interactions and identify only 8 studies testing such interventions. These studies estimate the impact of the interventions on the sibling bond, typically in small samples, without examining their effects on child skills. Examples include Siddiqui and Ross (2004), Kramer (2004), and Kennedy and Kramer (2008).

makes it possible to introduce a novel variable, "sibling bond," which captures how well siblings get along using information on the frequency and quality of sibling interactions, such as enjoying playtime together.

The paper presents two sets of results once siblings are incorporated into the study of skill formation. First, I provide reduced-form evidence that the quality of the sibling bond is relevant for understanding inequality across households. I document a socio-economic gradient in sibling bond and show that sibling bond at age 5 predicts better developmental, educational, and health outcomes across adolescence. Second, I estimate the joint technology of skill formation for younger and older siblings and find evidence consistent with the sibling bond being a productive input in both siblings' skill formation, alongside parent-child interactions, under the maintained identifying assumptions.

This paper points to several avenues for future research on family-based determinants of skill formation. One direction is to evaluate interventions that target the family as a whole – i.e., parents as well as siblings – for example through behavior-management programs aimed at fostering positive sibling interactions. Another is to examine whether broader policy domains, such as housing policy, may affect child development indirectly through sibling relationships, for example by reducing crowded living conditions that may limit privacy and increase conflict.

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A Appendices to "Skill Formation with Siblings"

A.1 Descriptive statistics

Table A1: Descriptive statistics on sample characteristics.

	Mean	St.Dev.	N
Female younger sibling	0.51	0.50	2558
Female older sibling	0.48	0.50	2558
Older sibling's Age	8.46	2.15	2558
Number of siblings (age-3 wave)	1.60	0.75	2558
Indicator variable for step sibling	0.004	0.07	2558
Mother's age at birth	30.51	5.03	2555
Mother education past compulsory (age-5 wave)	0.56	0.50	2558
Mother's mental health Kessler K6 Scale	2.77	3.48	2558
Years in current address	6.79	4.45	2558
Number of rooms in the house (age-3 wave)	6.18	1.59	2558

Note. The table presents the descriptive statistics on the sample. Mean (%) is reported in column 1, standard deviation is reported in column 2, and number of observations in column 3. Mother's mental health is measured with the Kessler 6. The Number of rooms in the house excludes bathrooms, toilets, halls, and garages.

A.2 Strengths and Difficulties Questionnaire (SDQ)

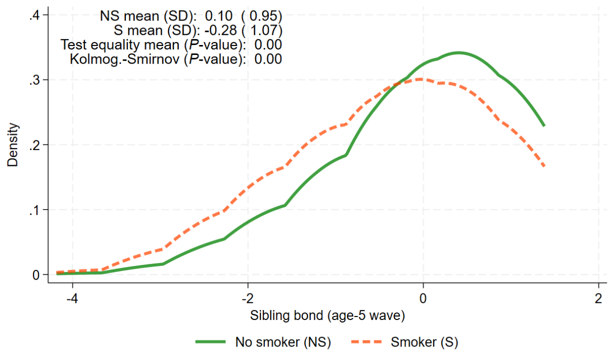
Table A2: Strengths and Difficulties Questionnaire (SDQ)

Strengths and Difficulties Questionnaire (SDQ) administered to the cohort member child and older sibling	
1. Considerate of other people's feelings^{+}	2. Restless, overactive and not able to sit still for long
3. Often complaining of headaches, stomach-aches or sickness	4. Sharing readily with other children (treats, toy, pencils etc.)$^{+}$
5. Has often had temper tantrums or hot tempers	6. Rather solitary, tending to play alone
7. Generally obedient, usually doing what adults requested^{+}	8. Many worries, often seeming worried
9. Helpful if someone was hurt, upset or feeling ill^{+}	10. Constantly fidgeting and squirming
11. Has had at least one good friend $^{+}$	12. Has often had fights with other children or bullies them
13. Often unhappy, downhearted or tearful	14. Generally liked by other children^{+}
15. Easily distracted, concentration wandered	16. Nervous or clingy in new situations, easily loses confidence
17. Kind to younger children $^{+}$	18. Often lies or cheats
19. Picked on or bullied by other children	20. Often volunteer to help (parents, teachers, other children)$^{+}$
21. Able to think things out before acting $^{+}$	22. Stole from home, school or elsewhere
23. Getting on better with adults than with other children	24. Many fears, easily scared
25. Has seen tasks through to the end, good attention span $^{+}$	

Note. The Strengths and Difficulties Questionnaire items are rated on three levels: 'Does not apply', 'Somewhat applies', 'Certainly applies'. Items indicating lower skills are reverse-coded so that higher values correspond to higher skills. Items denoted by $^{+}$ are positively coded in the original scale. The items measuring Emotional symptoms are 3, 8, 13, 16 and 24. The items measuring Conduct problems are 5, 7, 12, 18 and 22. The items measuring Hyperactivity/inattention are 2, 10, 15, 21 and 25. The items measuring Peer relationship problem are 6, 11, 14, 19 and 23. The items measuring Prosocial behavior are 1, 4, 9, 17 and 20. An item is excluded when over 95% of responses fall in one category, leaving under 5% in the other two combined (items 8, 13, 19, and 22). The same rule is applied across all measurement systems.

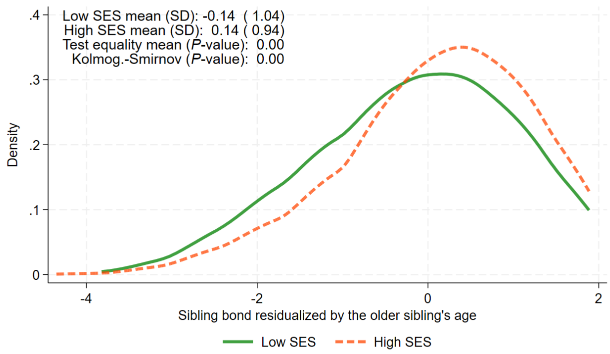
A.3 Descriptive evidence: additional results

Figure A1: Socio-economic gradient (mother was smoking during pregnancy) in the sibling bond



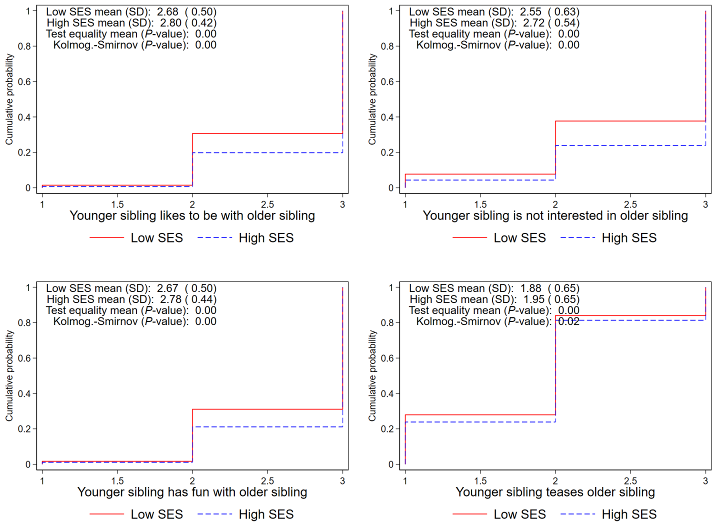
Note. The figure presents the socio-economic gradient in the quality of the sibling bond at the age-5 wave. The socio-economic status is a dummy equal to 1 if the mother was smoking during pregnancy. The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. The index of sibling bond is standardized to have mean 0 and standard deviation 1. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). Higher scores correspond to better quality interactions. I report the means of the quality of interactions by socio-economic gradient and their standard deviations (SD) between parentheses. The distribution is estimated nonparametrically, using an Epanechnikov kernel. I report the p-value of a t-test on the equality of means between the two groups assuming unequal variances. I report the p-value from Kolmogorov-Smirnov test on the equality between the distributions by socio-economic gradient.

Figure A2: Socio-economic gradient (mother's education) in the sibling bond residualized by the siblings' age gap



Note. The figure presents the socio-economic gradient in the quality of the sibling bond residualized by the siblings' age gap at the age-5 wave. The socio-economic status is the mother's education at the age-5 wave (dummy for whether the mother continued schooling past the minimum leaving age, based on her date of birth). The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. The index of sibling bond is standardized to have mean 0 and standard deviation 1. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). Higher scores correspond to better quality interactions. I report the means of the quality of interactions by socio-economic gradient and their standard deviations (SD) between parentheses. The distribution is estimated nonparametrically, using an Epanechnikov kernel. I report the p-value of a t-test on the equality of means between the two groups assuming unequal variances. I report the p-value from Kolmogorov-Smirnov test on the equality between the distributions by socio-economic gradient.

Figure A3: Cumulative distribution function: socio-economic gradient (mother's education) for each item used to measure sibling bond



Note. The figure presents the socio-economic gradient in each item used to measure the quality of sibling interactions at the age-5 wave. The socio-economic status is the mother's education at the age-5 wave (dummy for whether the mother continued schooling past the minimum leaving age, based on her date of birth). The mother is asked to answer the following 4 questions about how often [Never, Sometimes, Frequently] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). Higher scores correspond to a higher quality bond between siblings.

Table A3: Age-5 sibling bond and younger sibling's pooled development during adolescence (age 5-17)

Outcome	Externalizing		Internalizing		Cognitive	
	(1)	(2)	(3)	(4)	(5)	(6)
Sibling bond (age 5)	0.294***	0.110***	0.243***	0.069**	0.138***	0.033
	(0.032)	(0.028)	(0.031)	(0.027)	(0.028)	(0.026)
Observations	1397	1397	1316	1316	1749	1749
R^2	0.088	0.442	0.067	0.322	0.021	0.304
Younger & older sib's skills (age-3 wave)	No	Yes	No	Yes	No	Yes
Parental investment (age-5 wave)	No	Yes	No	Yes	No	Yes
Other controls	No	Yes	No	Yes	No	Yes

Note. The table presents the relationship between the age-5 sibling bond and the younger sibling's pooled development during adolescence (age 5-17). Variables are standardized to have mean 0 and standard deviation 1. The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). The parental investment index is obtained by summing the values from the questions asking the parents how often [Every day, Several times a week, Once or twice a week, Once or twice a month, Less often, Not at all] they do the following activities: (i) How often do you read to the child, (ii) How often tells stories to the child, (iii) How often does musical activities with the child, (iv) How often does the child paint/draw at home, (v) How often do you play physically active games with the child, (vi) How often play indoor games with the child, (vii) How often play outdoor games with the child, (viii) How often family does indoor activities together, (ix) How often child sees grandparents, (x) How often child sees other relatives, (xi) How often child spends time with friends outside school, (xii) How often ignores child when naughty, (xiii) How often smacks child when naughty, (xiv) How often shouts at child when naughty, (xv) How often sends child to bedroom/naughty chair, (xvi) How often takes away treats from child when naughty, (xvii) How often tells child off when naughty, (xviii) How often bribes child when naughty, (xix) How often tries to reason with child when naughty, (xx) How often makes sure child obeys instruction/request, (xxi) How close the bond between mother and child is. Other controls include mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, age gap between younger and older sibling, siblings' gender, housing tenure, years lived in current address, region fixed effects. Internalizing skill captures the ability to focus drive and determination to pursue a long-term goal. Externalizing skill captures the ability to engage in interpersonal activities. Robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

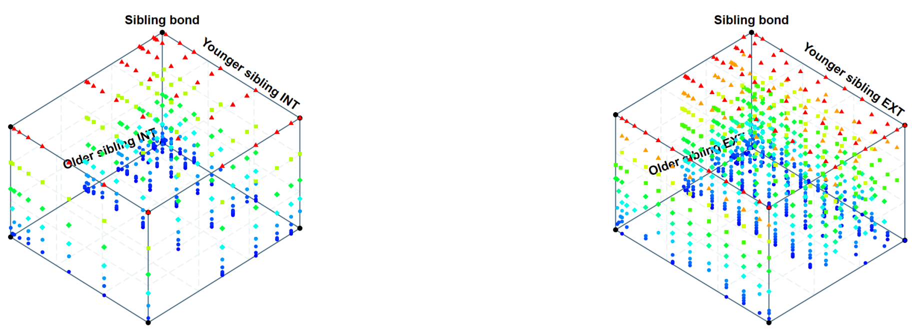
Table A4: Age-5 sibling bond and younger sibling's age-17 outcomes

Panel A: Outcome	Grade GCSE Math				Grade GCSE English			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Sibling bond (age 5)	0.307***	0.143***	0.144***	0.074	0.288***	0.133***	0.135***	0.095**
	(0.051)	(0.051)	(0.051)	(0.050)	(0.047)	(0.048)	(0.048)	(0.046)
Observations	1909	1909	1909	1909	1918	1918	1918	1918
R^2	0.025	0.147	0.147	0.259	0.026	0.146	0.147	0.270
Younger & older sib's skills (age-3 wave)		✓	✓	✓		✓	✓	✓
Parental investment (age-5 wave)			✓	✓			✓	✓
Other controls				✓				✓

Panel B: Outcome	Study for an A-level qualification (age 17)				Smoke cigarettes (age 17)			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Sibling bond (age 5)	0.061***	0.029**	0.030**	0.019	-0.038***	-0.035**	-0.036***	-0.026*
	(0.013)	(0.014)	(0.014)	(0.013)	(0.013)	(0.014)	(0.014)	(0.014)
Observations	2026	2026	2026	2026	2192	2192	2192	2192
R^2	0.013	0.083	0.085	0.172	0.005	0.014	0.015	0.035
Younger & older sib's skills (age-3 wave)		✓	✓	✓		✓	✓	✓
Parental investment (age-5 wave)			✓	✓			✓	✓
Other controls				✓				✓

Note. The table presents the relationship between the age-5 sibling bond and the younger sibling's educational and health outcomes at ages 17. The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). The sibling bond index is standardized to have mean 0 and standard deviation 1. The parental investment index is obtained by summing the values from the questions asking the parents how often [Every day, Several times a week, Once or twice a week, Once or twice a month, Less often, Not at all] they do the following activities: (i) How often do you read to the child, (ii) How often tells stories to the child, (iii) How often does musical activities with the child, (iv) How often does the child paint/draw at home, (v) How often do you play physically active games with the child, (vi) How often play indoor games with the child, (vii) How often play outdoor games with the child, (viii) How often family does indoor activities together, (ix) How often child sees grandparents, (x) How often child sees other relatives, (xi) How often child spends time with friends outside school, (xii) How often ignores child when naughty, (xiii) How often smacks child when naughty, (xiv) How often shouts at child when naughty, (xv) How often sends child to bedroom/naughty chair, (xvi) How often takes away treats from child when naughty, (xvii) How often tells child off when naughty, (xviii) How often bribes child when naughty, (xix) How often tries to reason with child when naughty, (xx) How often makes sure child obeys instruction/request, (xxi) How close the bond between mother and child is. Other controls include mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, age gap between younger and older sibling, siblings' gender, housing tenure, years lived in current address, region fixed effects. Internalizing skill captures the ability to focus drive and determination to pursue a long-term goal. Externalizing skill captures the ability to engage in interpersonal activities. GCSE stands for the General Certificate of Secondary Education, which is a qualification in a specific subject typically taken by school students aged 14-16 and is pre-requisite to study for an A-level qualification. The GCSE corresponds to a high school diploma in the United States. Students who plan to go to university study for an A-level qualification. Robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Figure A4: Sibling bond and siblings' socio-emotional skills



Note. The figures show the 3D-plot of the sibling bonds and siblings' skills. It presents descriptive evidence that there are children with poor socio-emotional skills, who still have quality interactions with their siblings, as well as siblings with good socio-emotional skills, who have low quality interactions with their siblings. The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling).

Table A5: Age-5 sibling bond and younger sibling's age-17 outcomes (full sample)

Panel A:	Grade GCSE Math		Grade GCSE English	
	(1)	(2)	(3)	(4)
Sibling bond (worst interaction for only child)	0.207***		0.104	
	(0.071)		(0.064)	
Sibling bond (best interaction for only child)		0.076		0.109**
		(0.051)		(0.047)
Observations	2514	2514	2519	2519
R^2	0.236	0.233	0.256	0.257
Younger & older sib's skills (age-3 wave)	✓	✓	✓	✓
Parental investment (age-5 wave)	✓	✓	✓	✓
Other controls	✓	✓	✓	✓

Panel B:	Study for A-level qualification (age 17)		Smoke cigarettes (age 17)	
	(1)	(2)	(3)	(4)
Sibling bond (worst interaction for only child)	0.032*		-0.056***	
	(0.019)		(0.020)	
Sibling bond (best interaction for only child)		0.022		-0.023
		(0.014)		(0.015)
Observations	2685	2685	2910	2910
R^2	0.167	0.167	0.030	0.027
Younger & older sib's skills (age-3 wave)	✓	✓	✓	✓
Parental investment (age-5 wave)	✓	✓	✓	✓
Other controls	✓	✓	✓	✓

Note. The table presents the relationship between the age-5 sibling bond and the younger sibling's educational and health outcomes at ages 14 and 17 for the full sample (children with and without siblings). For only children, the sibling bond and the older sibling's socio-emotional skills variables – both mechanically missing – are imputed separately at their respective sample minimum ("worst-case") and sample maximum ("best-case") values. Then in the regression, I control for the number of siblings and a dummy variable equal to 1 if the child is an only child. The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). The sibling bond index is standardized to have mean 0 and standard deviation 1. The parental investment index is obtained by summing the values from the questions asking the parents how often [Every day, Several times a week, Once or twice a week, Once or twice a month, Less often, Not at all] they do the following activities: (i) How often do you read to the child, (ii) How often tells stories to the child, (iii) How often does musical activities with the child, (iv) How often does the child paint/draw at home, (v) How often do you play physically active games with the child, (vi) How often play indoor games with the child, (vii) How often play outdoor games with the child, (viii) How often family does indoor activities together, (ix) How often child sees grandparents, (x) How often child sees other relatives, (xi) How often child spends time with friends outside school, (xii) How often ignores child when naughty, (xiii) How often smacks child when naughty, (xiv) How often shouts at child when naughty, (xv) How often sends child to bedroom/naughty chair, (xvi) How often takes away treats from child when naughty, (xvii) How often tells child off when naughty, (xviii) How often bribes child when naughty, (xix) How often tries to reason with child when naughty, (xx) How often makes sure child obeys instruction/request, (xxi) How close the bond between mother and child is. GCSE stands for the General Certificate of Secondary Education, which is a qualification in a specific subject typically taken by school students aged 14-16 and is pre-requisite to study for an A-level qualification. The GCSE corresponds to a high school diploma in the United States. Students who plan to go to university study for an A-level qualification. Other controls include mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, age gap between younger and older sibling, siblings' gender, housing tenure, years lived in current address, region fixed effects. Internalizing skill captures the ability to focus drive and determination to pursue a long-term goal. Externalizing skill captures the ability to engage in interpersonal activities. Robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Table A6: Correlation between the sibling bond and "home environment" variables

	Sibling bond	Parental investment	Calm home atmosphere	Close relationship mother and child	Mother's mental health	Household dual- or single-headed
Sibling bond	1.000					
Parental investment	0.080***	1.000				
Calm home atmosphere	0.126***	0.118***	1.000			
Close relationship mother and child	0.113***	0.222***	0.048**	1.000		
Mother's mental health	-0.223***	-0.115***	-0.187***	-0.090***	1.000	
Household dual- or single-headed	-0.120***	-0.022	-0.013	-0.011	0.138***	1.000

Note. The table shows the correlation between the sibling bond and parental investment, how calm the home atmosphere is, close relationship between mother and child, whether the household is dual or single head. The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). The parental investment index is obtained by summing the values from the questions asking the parents how often [Every day, Several times a week, Once or twice a week, Once or twice a month, Less often, Not at all] they do the following activities: (i) How often do you read to the child, (ii) How often tells stories to the child, (iii) How often does musical activities with the child, (iv) How often does the child paint/draw at home, (v) How often do you play physically active games with the child, (vi) How often play indoor games with the child, (vii) How often play outdoor games with the child, (viii) How often family does indoor activities together, (ix) How often child sees grandparents, (x) How often child sees other relatives, (xi) How often child spends time with friends outside school, (xii) How often ignores child when naughty, (xiii) How often smacks child when naughty, (xiv) How often shouts at child when naughty, (xv) How often sends child to bedroom/naughty chair, (xvi) How often takes away treats from child when naughty, (xvii) How often tells child off when naughty, (xviii) How often bribes child when naughty, (xix) How often tries to reason with child when naughty, (xx) How often makes sure child obeys instruction/request, (xxi) How close the bond between mother and child is. Both indexes of the sibling bond and parental investment are standardized to have mean 0 and standard deviation 1. *** p<0.01, ** p<0.05, * p<0.1.

Table A7: Age-5 sibling bond and younger sibling's age-14 actions

Outcome	Talk to sibling if worried		Talk to parents if worried		Argue with parents	
	(1)	(2)	(3)	(4)	(5)	(6)
Sibling bond (age 5)	0.025**	0.017	0.008	0.004	-0.104**	-0.094*
	(0.010)	(0.011)	(0.012)	(0.013)	(0.045)	(0.048)
Observations	2435	2435	2435	2435	2298	2298
R^2	0.003	0.033	0.000	0.018	0.003	0.036
Younger & older sib's skills (age-3 wave)	No	Yes	No	Yes	No	Yes
Parental investment (age-5 wave)	No	Yes	No	Yes	No	Yes
Other controls	No	Yes	No	Yes	No	Yes

Note. The table presents the relationship between the age-5 sibling bond and the younger sibling's actions at age 14. The sibling bond index is constructed by summing the values from the following 4 questions about how often [frequently, sometimes, never] the cohort member (i.e., the younger sibling): (i) Likes to be with the older sibling, (ii) Not much interested in the older sibling, (iii) Has a lot of fun with the older sibling, (iv) Teases or needles the older sibling. I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling). The sibling bond index is standardized to have mean 0 and standard deviation 1. The parental investment index is obtained by summing the values from the questions asking the parents how often [Every day, Several times a week, Once or twice a week, Once or twice a month, Less often, Not at all] they do the following activities: (i) How often do you read to the child, (ii) How often tells stories to the child, (iii) How often does musical activities with the child, (iv) How often does the child paint/draw at home, (v) How often do you play physically active games with the child, (vi) How often play indoor games with the child, (vii) How often play outdoor games with the child, (viii) How often family does indoor activities together, (ix) How often child sees grandparents, (x) How often child sees other relatives, (xi) How often child spends time with friends outside school, (xii) How often ignores child when naughty, (xiii) How often smacks child when naughty, (xiv) How often shouts at child when naughty, (xv) How often sends child to bedroom/naughty chair, (xvi) How often takes away treats from child when naughty, (xvii) How often tells child off when naughty, (xviii) How often bribes child when naughty, (xix) How often tries to reason with child when naughty, (xx) How often makes sure child obeys instruction/request, (xxi) How close the bond between mother and child is. Other controls include mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, age gap between younger and older sibling, siblings' gender, housing tenure, years lived in current address, region fixed effects. Internalizing skill captures the ability to focus drive and determination to pursue a long-term goal. Externalizing skill captures the ability to engage in interpersonal activities. Robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

A.4 Theoretical framework

This appendix presents a stylized model to highlight the trade-off faced by family i when deciding how to invest in the joint production of their children's human capital. The model is useful to derive the investment functions, which support the economic restrictions consistent with the exclusion restrictions discussed in detail in Section 2.5.

In standard models of human capital investment, it is assumed that parents care about their own consumption C_i and the development of an *only* child θ_i (e.g., Attanasio (2015)). I augment this standard framework by considering parents with *two* children and allow for sibling interactions (i.e., building a bond) as well as parent-child interactions. In turn, this theoretical framework speaks to the literature on intra-household allocation by highlighting that parents can invest in fostering the sibling bond to increase their children's skills – instead of only compensating or reinforcing differences in siblings' skills to trade off between equity and efficiency (e.g., Behrman et al. (1982) and Behrman (1988)).

I begin by defining human capital and pay particular attention to its multi-dimensionality by specifying three skill dimensions: internalizing (INT), externalizing (EXT), and cognitive (COG) skills for both the younger (Y) and older (O) siblings (c) in family i at time t. I formulate this problem as static and omit t from the model below to highlight the trade-off during this developmental stage. The model can be easily extended to multiple periods, where parents enjoy utility at different times, for example, to highlight the role of liquidity constraints or windows of opportunities in investment. Here, the model is kept simple to stress the role of siblings in the joint production of skills.

Parents optimize the expected utility function of consumption and siblings' skills, while facing a resource constraint (equations 8 and 9), the sibling bond (equation 10) and joint technology of skill formation (equations 11 and 12). Parents take the level of skills at the beginning of the period ($\theta_{i,0}$), generated by their previous investments, and the developmental shocks as given in the joint technology of skill formation.

$$\max_{C_i, PI_i} EU(C_i, \theta_{Y,i,1}, \theta_{O,i,1})$$

Subject to

$$L_i = 1 - PI_i \tag{8}$$

$$y_i + w_i L_i = C_i \tag{9}$$

$$SB_i = h(A_Y, A_O, e_i) \tag{10}$$

$$\theta_{Y,i,1} = f(\theta_{Y,i,0}, \theta_{O,i,0}, PI_i, SB_i, \mathbf{X}_i, v_{Y,i}) \tag{11}$$

$$\theta_{O,i,1} = g(\theta_{Y,i,0}, \theta_{O,i,0}, PI_i, SB_i, \mathbf{X}_i, u_{O,i}) \tag{12}$$

The parents of siblings Y and O can allocate their available time to work, L_i, as well as parental investment, PI_i, to improve their children's skills and sibling bond. Parental investment in the home environment is defined to encompass different types of activities, that promote the development of the child, such as material, time and parenting-style investment as well as joint activities. In the current framework, I focus on a composite measure of parental investment for ease of exposition and data availability, but the framework could be extended to accommodate these different dimensions of investment, for example, to consider the productivity-equity trade-off within the family (e.g., Behrman et al. (1982) and Behrman (1988)). w_i and y_i in the budget constraint are respectively the price and the non-work income (equation 9)

The sibling bond SB_i is a function of the siblings' actions, A_Y and A_O, and an idiosyncratic shock to their actions, e_i. Because parental investment PI_i enters siblings' pay-off functions, it affects the sibling bond indirectly by shifting siblings' equilibrium actions in the interaction game. The siblings' actions, A_Y and A_O, over the proposed unstructured activity aim to maximize the siblings' pay-off, $EU^c(A_Y, A_O, \xi_Y) = U(PI_i, A_Y, A_O, \xi_c)$, in a non-cooperative game, where they best respond to each other. These interactions can for example be modeled as a repeated dynamic game, where a sibling takes the first action, acting as a leader, and then the other sibling follows, as this would allow for role modeling.[2] Finally, e_i implies a non-deterministic link from parents' actions to the sibling bond, because parents may attempt to foster the sibling bond, yet the realized bond reflects siblings' endogenous responses to parental investment and may not materialize for reasons outside of the parents' control.

From this problem, it is possible to derive the following investment policy functions:

$$PI_i^* = l_t(\theta_{Y,i,0}, \theta_{O,i,0}, y_i, w_i, \mathbf{X}_i, \epsilon_{PI,i})$$

$$SB_i^* = n_t(\theta_{Y,i,0}, \theta_{O,i,0}, y_i, w_i, \mathbf{X}_i, \epsilon_{SB,i})$$

The investment equations are a function of preference parameters, productivity parameters, younger and older siblings' development at the beginning of the period, non-labor income y_i, prices w_i and the idiosyncratic shocks, $\epsilon_{PI,i}$ and $\epsilon_{SB,i}$.

Importantly, because both parental investment and sibling bond are jointly determined within the family's decision-making process, their policy functions are inherently interdependent. This potential simultaneity implies that observed measures of PI_i^* and SB_i^* are endogenous. To account for this, I model them as jointly determined endogenous variables within a structural system of equations and discuss in detail the identification of their respective impacts through the use of exclusion restrictions and appropriate instruments. This stylized model of parental investment guides the choice of exogenous shifters that could satisfy the exclusion restrictions, providing their *sufficient* conditions to be valid and consistent with economic theory. It is possible to infer from the model that the exogenous shifters are variables that do not enter the child's skill production function directly, but affect the child's skills only through the budget constraint.

[2] A similar extension to a dynamic Stackelberg game is considered in Del Boca et al. (2019), who instead study a model of child development where parents and children can invest in skills with partially altruistic parents acting as the Stackelberg leader and a child being the follower in setting their study time.

These correspond to variables related to prices and non-labor income. These conditions are only sufficient as the model cannot capture every possible response to unobserved shocks. Section 2.5 discusses the *necessary* conditions for the exogenous shifters to be valid and affect the child's skills only through parental investment and the sibling bond (Cunha et al., 2021).

A.5 Exploratory factor analysis

Table A8: Exploratory factor analysis of the siblings' socio-emotional skill questions

Item	Younger sibling (age 3)		Younger sibling (age 5)		Older sibling (age-3 wave)	
	Externalizing	Internalizing	Externalizing	Internalizing	Externalizing	Internalizing
Has at least one good friend	-0.052	**0.480**	0.060	**0.450**	0.135	**0.496**
Generally liked by other children	0.047	**0.482**	0.187	**0.485**	0.330	**0.507**
Often complains of headaches/sickness	0.144	**0.287**	-0.003	**0.369**	0.132	**0.325**
Nervous/clingy in new situations	-0.009	**0.495**	-0.068	**0.581**	-0.158	**0.646**
Has many fears, is easily scared	-0.060	**0.461**	0.017	**0.581**	-0.126	**0.671**
Solitary, plays alone	-0.078	**0.636**	-0.183	**0.640**	-0.089	**0.680**
Gets on better with adults than children	-0.038	**0.552**	0.013	**0.535**	0.027	**0.527**
Temper tantrums	**0.537**	0.105	**0.436**	0.253	**0.549**	0.151
Is generally obedient	**0.529**	0.092	**0.636**	-0.014	**0.655**	0.025
Fights with or bullies other children	**0.463**	0.186	**0.465**	0.263	**0.599**	0.171
Often lies or cheats	**0.536**	0.084	**0.451**	0.116	**0.473**	0.170
Restless, overactive, cannot stay still	**0.796**	-0.051	**0.748**	0.056	**0.854**	-0.109
Constantly fidgeting or squirming	**0.759**	-0.051	**0.649**	0.105	**0.794**	-0.015
Easily distracted, concentration wanders	**0.797**	-0.090	**0.805**	-0.055	**0.821**	-0.024
Thinks things out before acting	**0.334**	0.019	**0.654**	-0.120	**0.739**	-0.093
Sees tasks through to the end	**0.651**	-0.059	**0.773**	-0.156	**0.791**	-0.052

Note. The table displays the factor loadings obtained from exploratory factor analysis (EFA) of the siblings' socio-emotional skill questions. Two dimensions of socio-emotional skills are found: internalizing and externalizing, linked respectively to the ability to focus drive and determination to pursue long-term goals and the ability to engage in interpersonal activities. The EFA is based on the decomposition of the polychoric correlation matrix. The polychoric correlation is an estimate for the correlation between two normally distributed continuous random variables observed as ordinal variables. The solution is rescaled using oblique factor rotation obtained via the PROMAX protocol outlined in Hendrickson and White (1964) (with $k = 3$). Items indicating lower skills are reverse-coded so that higher values correspond to higher skills.

Table A9: Exploratory factor analysis: residualized sibling bond and parental investment

Item	Parental investment	Sibling bond
Younger sib likes to be with older sib	-0.018	**0.672**
Younger sib interested in older sib	-0.005	**0.442**
Younger sib has fun with older sib	0.004	**0.652**
Younger sib does not tease older sib	-0.030	**0.195**
How often do you read to child	**0.399**	-0.035
How often tells stories to child	**0.455**	0.026
How often does musical activities with child	**0.476**	0.045
How often does child paint/draw at home	**0.576**	-0.025
How often do you play physically active games with child?	**0.518**	0.016
Frequency play indoor games with child	**0.586**	-0.019
Frequency take child to park or playground	**0.373**	-0.046
How often family does indoor activities together	**0.280**	0.000
How often child sees grandparents	**0.000**	0.050
How often child sees other relatives	**0.050**	-0.015
How often child spends time with friends outside school	**0.171**	-0.011
How often ignores child when naughty	**-0.032**	0.016
How often smacks child when naughty	**-0.115**	0.002
How often shouts at child when naughty	**0.106**	0.034
How often sends child to bedroom/naughty chair	**-0.014**	-0.009
How often takes away treats from child when naughty	**-0.019**	0.009
How often tells child off when naughty	**0.052**	0.023
How often bribes child when naughty	**-0.015**	-0.042
How often tries to reason with child when naughty	**0.101**	-0.032
How often makes sure child obeys instruction/request	**0.057**	0.067
How close bond between mother and child	**0.148**	0.115

Note. The table reports the factor loadings from the exploratory factor analysis (EFA) based on items for sibling bond and parental investment residualized for siblings' gender, the age gap between the younger and older sibling, siblings' age-3 skills, mother's mental health, mother's education, mother's age, household structure, number of children, housing tenure, years lived at the current address, and region fixed effects. The EFA is based on the decomposition of the correlation matrix. The solution is rescaled using oblique factor rotation obtained via the PROMAX protocol (with $k = 3$). I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling).

Table A10: Exploratory factor analysis of the sibling bond, parental investment, age-5 younger sibling's internalizing and externalizing skill questions

Item	Sibling bond	Parental investment	Internalizing	Externalizing
Younger sib likes to be with older sib	**0.846**	0.004	-0.064	0.067
Younger sib interested in older sib	**0.663**	-0.025	-0.018	0.066
Younger sib has fun with older sib	**0.816**	0.052	-0.091	0.071
Younger sib does not tease older sib	**0.196**	-0.054	-0.075	0.396
How often do you read to child	0.039	**0.406**	0.037	0.053
How often tells stories to child	0.001	**0.510**	-0.030	-0.065
How often does musical activities with child	0.021	**0.541**	-0.016	-0.033
How often does child paint/draw at home	-0.036	**0.606**	-0.017	0.026
How often do you play physically active games with child?	0.090	**0.542**	0.057	-0.045
Frequency play indoor games with child	-0.011	**0.639**	-0.049	0.039
Frequency take child to park or playground	0.000	**0.390**	0.020	-0.096
How often family does indoor activities together	0.023	**0.340**	-0.028	0.051
How often child sees grandparents	-0.097	**0.072**	0.068	-0.022
How often child sees other relatives	-0.180	**0.141**	0.079	-0.061
How often child spends time with friends outside school	0.007	**0.206**	0.120	-0.052
How often ignores child when naughty	0.020	**-0.054**	-0.037	0.075
How often smacks child when naughty	0.062	**-0.165**	0.001	-0.213
How often shouts at child when naughty	-0.132	**0.115**	-0.038	0.439
How often sends child to bedroom/naughty chair	-0.021	**-0.070**	-0.044	0.253
How often takes away treats from child when naughty	-0.063	**-0.050**	-0.026	0.242
How often tells child off when naughty	-0.253	**0.076**	-0.114	0.597
How often bribes child when naughty	0.014	**-0.050**	0.018	-0.046
How often tries to reason with child when naughty	0.239	**0.088**	0.030	-0.401
How often makes sure child obeys instruction/request	0.163	**0.100**	0.064	0.040
How close bond between mother and child	0.098	**0.237**	0.100	0.164
Child often complains of headaches/sickness	-0.081	**0.064**	0.448	0.046
Child has many worries, often seems worried	-0.085	0.005	**0.787**	0.005
Child often unhappy,downhearted, tearful	-0.071	-0.009	**0.710**	0.078
Child nervous/clingy in new situations	-0.141	-0.039	**0.586**	-0.001
Child has many fears, is easily scared	-0.058	-0.002	**0.649**	0.054
Child is rather solitary, plays alone	0.110	0.043	**0.558**	-0.170
Child has at least one good friend	0.091	0.029	**0.322**	0.088
Child generally liked by other children	0.062	0.032	**0.453**	0.198
Child picked on or bullied by other children	0.055	-0.074	**0.474**	0.115
Child gets on better with adults than children	0.227	-0.080	**0.395**	0.054
Child often has temper tantrums	-0.026	-0.015	0.228	**0.540**
Child is generally obedient	0.111	0.041	-0.055	**0.623**
Child fights with or bullies other children	0.069	-0.095	0.275	**0.543**
Child often lies or cheats	-0.050	-0.001	0.113	**0.556**
Child steals from home, school, elsewhere	-0.011	0.051	-0.046	**0.460**
Child is restless, overactive, cannot stay still	0.137	-0.056	0.096	**0.640**
Child constantly fidgeting or squirming	0.043	-0.050	0.166	**0.569**
Child is easily distracted, concentration wanders	0.064	-0.020	0.042	**0.675**
Child thinks things out before acting	0.048	0.055	-0.113	**0.590**
Child sees tasks through to the end	0.064	0.049	-0.110	**0.660**

Note. The table displays the factor loadings obtained from exploratory factor analysis (EFA) with the questionnaire items for parental investment, sibling bond, younger sibling's internalizing and externalizing skills at age 5. The EFA is based on the decomposition of the correlation matrix. The solution is rescaled using oblique factor rotation obtained via the PROMAX protocol (with $k = 3$). I recode behaviors indicating worse interactions in reverse (i.e., not much interested in older sibling and teases or needles older sibling).

Table A11: Scale reliability: Cronbach's alpha

Latent factor	**Cronbach's alpha**
Younger sib's internalizing (age 3)	0.532
Younger sib's internalizing (age 5)	0.563
Older sibling's internalizing (age-3 wave)	0.629
Younger sib's externalizing (age 3)	0.776
Younger sib's externalizing (age 5)	0.792
Older sibling's externalizing (age-3 wave)	0.835
Parental investment	0.581
Sibling bond	0.584

Note. The table presents Cronbach's alpha which measures how closely related a set of items are as a group for each latent factor. The Cronbach's alpha is computed as follows: $\frac{Nc}{(v+(N-1)c)}$ where N corresponds to the number of items, v is average variance of the items and c is the average inter-item correlation of the items. Cronbach's alpha can take values between 0 and 1 where values closer to 1 correspond to higher reliability. Values above 0.50 are considered acceptable (Taber, 2018).

A.6 Measurement invariance between siblings' skill measures

This section outlines a novel measurement challenge faced when estimating the joint technology of skill formation with siblings. As I am estimating the joint technology of the younger and older siblings' skills, I would like to set the same metric to compare the structural estimates of their joint skill formation technology.

This requires the socio-emotional questionnaire items to have the same relationship with the latent constructs across the younger and older siblings. In other words, the socio-emotional questionnaire items in the factor model must be invariant to the group, in this case between siblings. If invariance is not achieved, this would mean that the measures of the siblings' latent socio-emotional skills are on different scales and therefore incomparable. For example, this happens when some questions contribute more to the younger sibling's socio-emotional skills, while at the same time these questions contribute less to the older sibling's socio-emotional skills.

This can be tested via the psychometric measurement invariance developed by Vandenberg and Lance (2000), Putnick and Bornstein (2016), and Wu and Estabrook (2016). This test involves the estimation of a series of more restrictive measurement systems and the comparison of their fits to investigate whether questions are answered consistently across groups and therefore are invariant to the group.[3] Following the assumptions introduced by Wu and Estabrook (2016), the test compares the baseline model, namely the minimal identifiable model, with a series of models with stronger restrictions on the item- and sibling-specific intercepts and loadings, requiring them to be the same across groups. Their fit is then compared to see if the models with stronger restrictions have a worse fit. If the fit is not worse, then measurement invariance is not rejected.

[3]Versions of this test have now been used in economics by Attanasio et al. (2020), Attanasio et al. (2025), and Heckman and Zhou (2022).

I estimate three models with additional restrictions and compare their relative fit to the baseline model. First, a threshold invariant model is estimated where the thresholds are restricted to be the same across the younger and older sibling ($\tau_{1,YSjt} = \tau_{1,OSjt}$, $\tau_{2,YSjt} = \tau_{2,OSjt}$, $\mu_{\theta,YSt} = \mu_{\theta,OSt} = 0$, $\sigma_{\theta,YSt} = \sigma_{\theta,OSt} = 1\ \forall j,t$). This is observationally equivalent to the baseline model when each item is a categorical variable with three categories (Wu and Estabrook, 2016). Second, the loading- and threshold-invariant model is estimated, imposing stronger restrictions on the factor loadings and the thresholds of the items, which must be the same across siblings ($\tau_{1,YSjt} = \tau_{1,OSjt}$, $\tau_{2,YSjt} = \tau_{2,OSjt}$, $\lambda_{YSjt} = \lambda_{OSjt}$, $\mu_{\theta,YSt} = \mu_{\theta,OSt} = 0$, $\sigma_{\theta,YSt} = 1\ \forall j,t$). This requires the SDQ items to have the same relationship with the latent skill across groups. Third, a loading-, threshold-, and intercept-invariant model is estimated. This model imposes the factor loadings, the intercepts and the thresholds to be the same across siblings ($\tau_{1,YSjt} = \tau_{1,OSjt}$, $\tau_{2,YSjt} = \tau_{2,OSjt}$, $\lambda_{YSjt} = \lambda_{OSjt}$, $\alpha_{YSjt} = \alpha_{OSjt} = 0$, $\mu_{\theta,YSt} = 0$, $\sigma_{\theta,YSt} = 1\ \forall j,t$).

The measurement invariance test involves the comparison of models' fits after the inclusion of these additional restrictions. The comparison of χ^2 across models is however not recommended because tests based on $\Delta\chi^2$ are known to display high Type I error rates with large sample size and complex models (Sass et al., 2014). The psychometric literature recommends a holistic approach by using approximate fit indices (AFIs). These indices successfully adjust for model complexity (Cheung and Rensvold, 2002), but they do not have a known sampling distribution. Therefore, it is necessary to rely on simulation studies to derive the rule of thumb indicating what level of ΔAFI is compatible with invariance.

I present the χ^2 statistic as well as other alternative goodness-of-fit indices commonly used, such as the root mean squared error of approximation (RMSEA), standardized root mean square residual (SRMSR), the comparative fit index (CFI), and the Tucker-Lewis index (TLI). Commonly-used rules of thumb for comparison of fit are Chen (2007) who suggests the following thresholds for *rejecting* measurement invariance: ΔRMSEA>0.015, ΔCFI<-0.010, and ΔSRMSR>0.010. Chen (2007) computes these rules of thumb from simulations with continuous measures and may not adjust well to the categorical case as suggested by Lubke and Muthén (2004). Rutkowski and Svetina (2017) find that a ΔRMSEA threshold of 0.010 is appropriate for testing equality of slopes and thresholds.

Appendix Table A12 presents the fit of each model. The baseline model fits the data well. Restricting the thresholds and loadings to be the same across siblings yields a fit comparable to the baseline model. The fit however worsens when I also restrict the intercepts to be the same, but still provides a comparable fit according to the measures above. Overall, these results support the invariance of latent socio-emotional skills between younger and older siblings and indicate that they are measured on the same scale across the two groups, thereby strengthening confidence in the comparison of the estimated joint skill production functions for younger and older siblings.

Table A12: Comparison of models' fit for measurement invariance

		Absolute fit				
	N of Parameters	χ^2	RMSEA	SRMSR	CFI	TLI
Baseline model/ Threshold Invariance	98	2339.833	0.064	0.084	0.949	0.940
Threshold and loading invariance	84	2693.985	0.066	0.089	0.941	0.935
Threshold, loading, and intercept invariance	70	3276.389	0.071	0.093	0.927	0.925

	Relative Fit to the Baseline model/Threshold Invariance				
	P-value	Δ RMSEA	Δ SRMSR	Δ CFI	Δ TLI
Threshold and loading invariance	0.000	0.002	0.005	-0.008	-0.005
Threshold, loading, and intercept invariance	0.000	0.007	0.009	-0.022	-0.015

Note. The table displays a comparison of models' fit for measurement invariance. RMSEA stands for the root mean squared error of approximation, SRMR for the standardised root mean square residual, CFI for the comparative fit index, and TLI for the Tucker-Lewis index.

A.7 Measurement system with continuous, binary, and categorical items

This section presents a unified measurement system for continuous, binary, and ordered categorical items. Let m^*_{ijt} denote the latent response for item j, child i, at time t. Suppressing the child index for ease of exposition, the latent response is assumed to satisfy

$$m^*_{ijt} = \alpha_{jt} + \lambda_{jt}^{\top} \ln \theta_{it} + \varepsilon_{ijt}, \tag{13}$$

where α_{jt} is an item-specific intercept, λ_{jt} is a vector of factor loadings, and ε_{ijt} is an idiosyncratic measurement error independent of the latent factors.

The distinction across item types lies in how the observed response m_{ijt} is linked to the latent response m^*_{ijt}:

(i) **Continuous items.** The observed item coincides with the latent response:

$$m_{ijt} = m^*_{ijt}.$$

In this case, the standard factor model applies directly to the observed data.

(ii) **Binary items.** The observed response is generated by thresholding the latent response at zero:

$$m_{ijt} = \mathbf{1}\{m^*_{ijt} \geq 0\}.$$

Equivalently,

$$\Pr(m_{ijt} = 1 \mid \theta_{it}) = \Pr(m^*_{ijt} \geq 0 \mid \theta_{it}).$$

Under a normality assumption for ε_{ijt}, this is the usual probit item-response model.

(iii) **Ordered categorical items.** The observed response takes values $m_{ijt} \in \{1, \ldots, L\}$ according to intervals of the latent response:

$$m_{ijt} = l \quad \Longleftrightarrow \quad \tau_{l-1,jt} < m^*_{ijt} \leq \tau_{l,jt}, \qquad l = 1, \ldots, L,$$

where $\tau_{0,jt} = -\infty$, $\tau_{L,jt} = +\infty$, and $\tau_{1,jt} < \cdots < \tau_{L-1,jt}$ are item-specific thresholds. Hence,

$$\Pr(m_{ijt} = l \mid \theta_{it}) = \Pr\Big(\tau_{l-1,jt} < m^*_{ijt} \leq \tau_{l,jt} \mid \theta_{it}\Big).$$

Model (i) corresponds to the measurement systems used in Cunha et al. (2010), Attanasio et al. (2020), and Attanasio et al. (2020). Model (ii) is the binary-response special case of an item response model. Model (iii), which is the specification adopted in this paper, generalizes the binary case by allowing multiple thresholds rather than a single cutoff.

What changes when indicators are categorical? Relative to the continuous-item case, estimation with binary or ordered categorical indicators introduces an additional latent-response layer. The object satisfying the factor structure in (13) is not the observed item m_{ijt}, but the unobserved continuous response m^*_{ijt}. The observed categories only reveal the interval of m^*_{ijt} delimited by item-specific thresholds.

This has three main implications for estimation. First, the model includes threshold parameters $\{\tau_{l,jt}\}$, one fewer than the number of categories for each item, which must be estimated jointly with factor loadings and other measurement parameters. In the binary case there is only one threshold, so the ordered categorical model nests the binary model as a special case. In the continuous case there are no thresholds because the latent response is directly observed.

Second, because the observed ordinal variables do not have meaningful cardinal units, the scale of the latent response must be normalized. For categorical indicators, identification is achieved by fixing the location and scale of m^*_{ijt}, typically through restrictions on the thresholds and/or by normalizing the variance of ε_{ijt} (for example, to one in a probit formulation). This differs from the continuous case, where the observed variance provides scale information directly and identification is typically obtained by fixing one loading or factor variance. With categorical items, the factor scale and the threshold scale cannot both be free.

Third, the sample moments used in estimation differ. With continuous indicators, estimation relies on means, variances, and covariances of observed responses. With ordered categorical indicators, the relevant dependence structure is instead recovered from the latent responses underlying the categories. In practice this is done using polychoric correlations for pairs of ordinal items. The algorithm therefore differs from the continuous-item case because it must account for the discretization step.

In summary, moving from continuous to categorical indicators does not change the underlying factor-analytic logic, but it changes the mapping from latent responses to observed data, introduces threshold parameters, requires location-scale normalizations for the latent response, and modifies the estimation routine to accommodate ordinal rather than cardinal measurements.

A.8 Balance check

Table A13: Balance table: cohort member's pre-determined characteristics at birth

Outcome	**Number of siblings**		**Mother's mental health**		**Mother employed before pregnancy**		**Public transport in area**		**Months lived in current address**	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Number of rooms (t-1)	0.023***	0.004	-0.099***	-0.013	0.015**	-0.013	-0.045***	-0.020	-0.990	-0.690
	(0.008)	(0.007)	(0.024)	(0.024)	(0.007)	(0.008)	(0.016)	(0.018)	(0.731)	(0.587)
Local female employment rate	-0.006**	-0.004	-0.004	0.004	0.003	0.002	-0.010**	0.032**	-0.483**	-0.420
	(0.003)	(0.005)	(0.008)	(0.020)	(0.002)	(0.006)	(0.005)	(0.013)	(0.224)	(0.491)
Observations	2220	2220	2220	2220	2220	2220	2220	2220	2220	2220
Other controls	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes

Note. The table presents the balance checks for the exogenous shifters on the cohort member's pre-determined characteristics at birth (age-0 wave). Odd columns do *not* include any controls, while even columns include other controls. Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual- or single-headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

A.9 Placebo check

Table A14: Number of rooms and only child's development

Outcome	Externalizing		Internalizing		Cognitive	
	(1)	(2)	(3)	(4)	(5)	(6)
Number of rooms (t-1)	0.273***	-0.044	0.125***	0.030	0.750***	-0.264
	(0.065)	(0.055)	(0.039)	(0.037)	(0.245)	(0.221)
Observations	1081	1081	1081	1081	1081	1081
R^2	0.019	0.464	0.012	0.279	0.012	0.217
Controls	No	Yes	No	Yes	No	Yes

Note. The table presents placebo regressions of only children's skills at age 5 on the number of rooms in the household at age 3. Since only children do not have a sibling bond by construction, any association between the number of rooms and child development in this sample cannot operate through sibling interactions. Columns (1), (3), and (5) report specifications without additional controls; columns (2), (4), and (6) add baseline child and household controls. Other controls include mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, housing tenure, years lived in current address, region fixed effects. Internalizing skill captures the ability to focus drive and determination to pursue a long-term goal. Externalizing skill captures the ability to engage in interpersonal activities. Robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

A.10 Heterogeneity: investment functions

Table A15: Investment functions: Sibling bond & parental investment by the older sibling's gender

Older sibling's gender	**Female**		**Male**	
Outcome	**Sibling bond**	**Parental investment**	**Sibling bond**	**Parental investment**
	(1)	(2)	(3)	(4)
Number of rooms (t-1)	0.059**	0.000	0.076***	0.015
	(0.024)	(0.019)	(0.025)	(0.017)
Local female employment rate	-0.017	0.051***	-0.021	0.032***
	(0.019)	(0.015)	(0.018)	(0.012)
Test of joint significance: F-statistic				
Number of rooms (t-1)	5.842		9.159	
Local female employment rate		11.251		6.879
Observations	1216	1216	1342	1342
Controls for siblings' skills	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes

Note. The table presents the structural estimates of the investment functions by the older sibling's gender. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include younger sibling's externalizing, internalizing and cognitive skill at $t-1$, older sibling's externalizing and internalizing, siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual- or single-headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Table A16: Investment functions: Sibling bond & parental investment by the younger sibling's gender

Younger sibling's gender	**Female**		**Male**	
Outcome	**Sibling bond**	**Parental investment**	**Sibling bond**	**Parental investment**
	(1)	(2)	(3)	(4)
Number of rooms (t-1)	0.110***	0.012	0.064**	-0.003
	(0.030)	(0.019)	(0.031)	(0.017)
Local female employment rate	-0.037	0.032**	-0.019	0.059***
	(0.023)	(0.012)	(0.024)	(0.017)
Test of joint significance: F-statistic				
Number of rooms (t-1)	13.031		4.190	
Local female employment rate		6.493		12.558
Observations	1312	1312	1245	1245
Controls for siblings' skills	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes

Note. The table presents the structural estimates of the investment functions by the younger sibling's gender. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include younger sibling's externalizing, internalizing and cognitive skill at $t-1$, older sibling's externalizing and internalizing, siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual- or single-headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Table A17: Investment functions: Sibling bond & parental investment by the siblings' gender composition

Siblings' gender composition	Mixed		Same	
Outcome	**Sibling bond**	**Parental investment**	**Sibling bond**	**Parental investment**
	(1)	(2)	(3)	(4)
Number of rooms (t-1)	0.074***	0.043**	0.066**	-0.026
	(0.022)	(0.017)	(0.028)	(0.018)
Local female employment rate	-0.002	0.024*	-0.035*	0.067***
	(0.017)	(0.013)	(0.020)	(0.013)
Test of joint significance: F-statistic				
Number of rooms (t-1)	11.116		5.580	
Local female employment rate		3.339		24.931
Observations	1266	1266	1292	1292
Controls for siblings' skills	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes

Note. The table presents the structural estimates of the investment functions by the siblings' gender composition. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include younger sibling's externalizing, internalizing and cognitive skill at $t-1$, older sibling's externalizing and internalizing, siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual- or single-headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

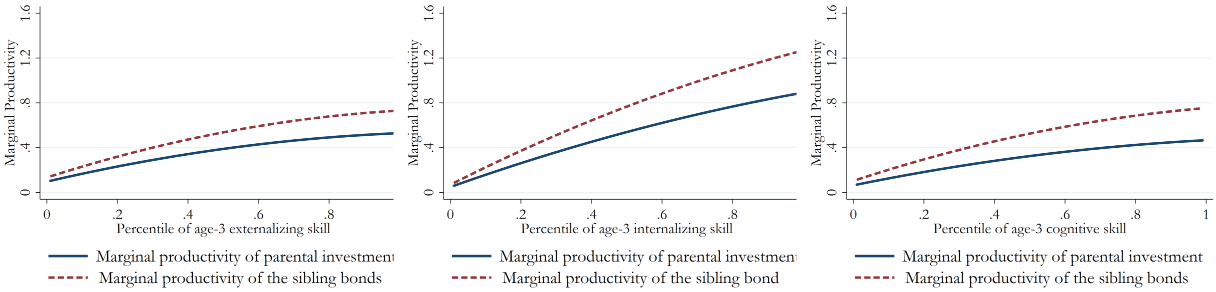
Table A18: Investment functions: Sibling bond & parental investment by the siblings' age gap

Siblings' age gap	Small		Large	
Outcome	**Sibling bond**	**Parental investment**	**Sibling bond**	**Parental investment**
	(1)	(2)	(3)	(4)
Number of rooms (t-1)	0.072***	0.019	0.072***	0.000
	(0.023)	(0.016)	(0.026)	(0.021)
Local female employment rate	-0.035*	0.038***	0.006	0.053***
	(0.018)	(0.012)	(0.019)	(0.015)
Test of joint significance: F-statistic				
Number of rooms (t-1)	9.717		7.689	
Local female employment rate		9.107		12.420
Observations	1573	1573	985	985
Controls for siblings' skills	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes

Note. The table presents the structural estimates of the investment functions by the siblings' age gap. Small age gap corresponds to siblings with an age gap below or equal to 3 years old (median age gap), age gap corresponds to siblings with an age gap above 3 years o Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include younger sibling's externalizing, internalizing and cognitive skill at $t-1$, older sibling's externalizing and internalizing, siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual- or single-headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

A.11 Marginal productivity

Figure A5: Marginal productivity of investment and sibling bond



Note. The figures present the marginal productivity of parental investment and sibling bond at age 5 by the age-3 skill levels. The marginal productivity of parental investment (sibling bond) is constructed using the estimates of the production function, evaluated at each percentile of the age-3 skill, while holding sibling bond (parental investment) at the age-3 skill percentile-specific mean and the other inputs at the median in the sample. The y-axis represents the marginal productivity of the input, in standard deviation units, of increasing the input by one standard deviation.

A.12 Joint technology of skill formation: exogenous investments

Table A19: Joint technology of skill formation: younger & older siblings - exogenous investments

Outcome	Externalizing (EXT)				Internalizing (INT)				Cognitive (COG)	
	Younger		Older		Younger		Older		Younger	
	Restricted	Unrestricted	Restricted	Unrestricted	Restricted	Unrestricted	Restricted	Unrestricted	Restricted	Unrestricted
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Younger sib's EXT skill (t-1)	0.696***	0.681***	-0.092***	-0.096***	0.005	-0.004	-0.020	-0.036*	0.082***	0.085***
	(0.037)	(0.037)	(0.018)	(0.019)	(0.015)	(0.015)	(0.021)	(0.021)	(0.022)	(0.022)
Younger sib's INT skill (t-1)	-0.134***	-0.134***	-0.057	-0.052	0.831***	0.806***	-0.233***	-0.233***	-0.005	-0.005
	(0.051)	(0.051)	(0.054)	(0.053)	(0.100)	(0.097)	(0.068)	(0.067)	(0.063)	(0.062)
Younger sib's COG skill (t-1)	0.089***	0.084***	0.029	0.031*	-0.019	-0.022	0.055**	0.051**	0.590***	0.594***
	(0.018)	(0.018)	(0.018)	(0.019)	(0.016)	(0.016)	(0.022)	(0.022)	(0.028)	(0.028)
Older sib's EXT skill (t-1)	0.004	-0.023	0.770***	0.766***	-0.032**	-0.044***	-0.116***	-0.138***	0.015	0.022
	(0.015)	(0.015)	(0.034)	(0.034)	(0.013)	(0.014)	(0.020)	(0.020)	(0.018)	(0.019)
Older sib's INT skill (t-1)	0.008	-0.003	0.012	0.011	0.020	0.015	0.987***	0.969***	-0.044	-0.040
	(0.031)	(0.032)	(0.034)	(0.034)	(0.028)	(0.029)	(0.088)	(0.087)	(0.042)	(0.042)
Parental investment (t)	0.052***	0.049***	0.068***	0.013	-0.026***	-0.028***	0.020	0.017	0.013	0.014
	(0.010)	(0.014)	(0.014)	(0.010)	(0.009)	(0.009)	(0.012)	(0.012)	(0.012)	(0.012)
Sibling bond (t)		0.099***		0.067***		0.046***		0.079***		-0.025
		(0.011)		(0.014)		(0.013)		(0.018)		(0.018)
Observations	2558	2558	2475	2475	2558	2558	2475	2475	2558	2558
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note. This table presents the estimates of the joint technology when parental investment and sibling bond are treated as exogenous. Younger sibling at age 5, older sibling between age 6 and 15. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual- or single-headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

A.13 Robustness: families with more than two siblings

Table A20: Joint technology of skill formation: average sibling bond with more than two siblings

Outcome	Externalizing (EXT)		Internalizing (INT)		Cognitive (COG)
	Younger	Older	Younger	Older	Younger
	(1)	(2)	(3)	(4)	(5)
Younger sibling's EXT skill (t-1)	0.499***	-0.013	-0.111**	-0.100*	-0.096
	(0.091)	(0.057)	(0.053)	(0.054)	(0.085)
Younger sibling's INT skill (t-1)	-0.325***	-0.268**	0.751***	-0.318***	-0.205
	(0.105)	(0.112)	(0.115)	(0.094)	(0.134)
Younger sibling's COG skill (t-1)	0.083***	0.039	-0.033	0.048*	0.589***
	(0.029)	(0.029)	(0.021)	(0.026)	(0.037)
Older sibling's EXT skill (t-1)	-0.188**	0.592***	-0.164***	-0.221***	-0.225**
	(0.078)	(0.081)	(0.058)	(0.062)	(0.094)
Older sibling's INT skill (t-1)	-0.010	-0.013	-0.020	0.940***	-0.076
	(0.052)	(0.057)	(0.041)	(0.089)	(0.068)
Average sibling bond (t)	0.461**	0.461**	0.397**	0.284	0.657**
	(0.212)	(0.233)	(0.167)	(0.173)	(0.283)
Parental investment (t)	0.480**	0.627***	0.200	0.227	0.415
	(0.220)	(0.222)	(0.162)	(0.162)	(0.277)
Observations	2558	2475	2558	2475	2558
Other controls	Yes	Yes	Yes	Yes	Yes

Note. The table reproduces Table 3 by using the average of the sibling bonds from each sibling combination when the younger sibling has at least two older siblings. Younger sibling at age 5, older sibling between age 6 and 15. The average sibling bond is the average of the sibling bonds in families with more than two siblings. Columns 1-2 present the structural estimates for externalizing skill (ability to engage in interpersonal activities), Columns 3-4 for internalizing skill (ability to focus and pursue long-term goals), and Columns 5 for cognitive skill (ability to learn and solve tasks). The measurement system and the outcome equation are estimated jointly (Muthén, 1984). The F-stat on sibling bond is 10.896, F-stat on parental investment is 24.550. Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, housing tenure, years lived in current address, local employment rate at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

A.14 Robustness: family size & fertility

Table A21: Joint technology of skill formation: family size & fertility

Outcome	Externalizing (EXT)		Internalizing (INT)		Cognitive (COG)
	Younger	Older	Younger	Older	Younger
	(1)	(2)	(3)	(4)	(5)
Younger sibling's EXT skill (t-1)	0.551***	-0.350***	-0.029	-0.042	-0.050
	(0.066)	(0.071)	(0.036)	(0.041)	(0.059)
Younger sibling's INT skill (t-1)	-0.324***	-0.398**	0.839***	-0.240**	-0.172
	(0.105)	(0.168)	(0.122)	(0.095)	(0.128)
Younger sibling's COG skill (t-1)	0.088**	-0.098	0.046	0.108***	0.593***
	(0.043)	(0.072)	(0.032)	(0.037)	(0.050)
Older sibling's EXT skill (t-1)	-0.177***	0.360***	0.051	-0.067	-0.160**
	(0.062)	(0.118)	(0.049)	(0.055)	(0.081)
Older sibling's INT skill (t-1)	-0.010	-0.090	0.011	0.961***	-0.074
	(0.050)	(0.097)	(0.040)	(0.091)	(0.061)
Sibling bond (t)	0.418***	1.139***	-0.135	-0.121	0.454**
	(0.140)	(0.286)	(0.106)	(0.115)	(0.178)
Parental investment (t)	0.408**	0.510***	0.107	0.166	0.290
	(0.177)	(0.177)	(0.117)	(0.136)	(0.214)
Number of siblings (t)	0.098	-0.671*	0.491***	0.416**	0.079
	(0.238)	(0.343)	(0.169)	(0.188)	(0.278)
Observations	2558	2475	2558	2475	2558
Other controls	Yes	Yes	Yes	Yes	Yes

Note. The table reproduces the estimates for Table 3, instrumenting family size with the siblings' gender composition. Younger sibling at age 5, older sibling between age 6 and 15. Columns 1-2 present the structural estimates for externalizing skill (ability to engage in interpersonal activities), Columns 3-4 for internalizing skill (ability to focus and pursue long-term goals), and Columns 5 for cognitive skill (ability to learn and solve tasks). The measurement system and the outcome equation are estimated jointly (Muthén, 1984). Family size is instrumented using the gender composition of the siblings (Angrist et al., 2010). The F-stat on sibling bond is 9.485, F-stat on parental investment is 25.188, F-stat on number of siblings is 0.465. Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, housing tenure, years lived in current address, local employment rate at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

A.15 Translog production function

Table A22: Translog joint technology of skill formation

	Externalizing (EXT)				Internalizing (INT)				Cognitive (COG)	
	Younger	Younger	Older	Older	Younger	Younger	Older	Older	Younger	Younger
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Younger sib's EXT skill (t-1)	1.086***	1.086***	0.004	0.006	0.035	0.035	0.004	0.005	0.181	0.180
	(0.102)	(0.102)	(0.232)	(0.232)	(0.039)	(0.039)	(0.151)	(0.151)	(0.155)	(0.155)
Younger sib's INT skill (t-1)	-0.192*	-0.190*	-0.063	-0.058	0.837***	0.838***	-0.069	-0.066	-0.187	-0.189
	(0.103)	(0.103)	(0.265)	(0.265)	(0.042)	(0.042)	(0.172)	(0.173)	(0.156)	(0.157)
Younger sib's COG skill (t-1)	0.116	0.134	0.332*	0.380*	-0.057*	-0.049	0.006	0.038	0.675***	0.651***
	(0.076)	(0.091)	(0.199)	(0.224)	(0.030)	(0.037)	(0.134)	(0.154)	(0.134)	(0.133)
Older sib's EXT skill (t-1)	-0.059	-0.074	0.533***	0.496**	-0.072**	-0.078**	-0.104	-0.130	-0.082	-0.063
	(0.083)	(0.089)	(0.191)	(0.211)	(0.032)	(0.034)	(0.120)	(0.134)	(0.137)	(0.158)
Older sib's INT skill (t-1)	0.026	0.034	0.281	0.302	-0.018	-0.015	0.537***	0.550***	0.064	0.053
	(0.112)	(0.114)	(0.295)	(0.299)	(0.046)	(0.046)	(0.202)	(0.203)	(0.157)	(0.161)
Parental investment (t)	0.069***	0.068***	0.080**	0.079**	-0.025***	-0.025***	0.040*	0.039*	0.017	0.018
	(0.014)	(0.014)	(0.033)	(0.034)	(0.005)	(0.005)	(0.022)	(0.022)	(0.018)	(0.018)
Sibling bond (t)	0.078	0.043	-0.197	-0.291	0.170*	0.154	0.021	-0.042	0.356	0.403
	(0.236)	(0.261)	(0.563)	(0.607)	(0.098)	(0.108)	(0.356)	(0.394)	(0.328)	(0.343)
Parental investment (t) * Sibling bond (t)		-0.075		-0.197		-0.033		-0.133		0.099
		(0.203)		(0.478)		(0.079)		(0.336)		(0.294)
Younger sib's EXT skill (t-1) * Sibling bond (t)	0.063	0.096	-0.094	-0.005	0.028	0.043	0.062	0.123	0.166	0.121
	(0.080)	(0.116)	(0.219)	(0.310)	(0.032)	(0.048)	(0.137)	(0.209)	(0.126)	(0.174)
Younger sib's INT skill (t-1) * Sibling bond (t)	-0.152	-0.141	-0.136	-0.108	-0.043	-0.038	0.155	0.174	-0.293	-0.307
	(0.164)	(0.167)	(0.402)	(0.409)	(0.064)	(0.065)	(0.268)	(0.274)	(0.257)	(0.268)
Younger sib's COG skill (t-1) * Sibling bond (t)	0.112	0.131	0.473*	0.522*	-0.001	0.007	-0.014	0.019	0.043	0.019
	(0.105)	(0.117)	(0.272)	(0.289)	(0.042)	(0.047)	(0.182)	(0.197)	(0.181)	(0.177)
Older sib's EXT skill (t-1) * Sibling bond (t)	-0.078	-0.091	-0.386*	-0.420**	-0.000	-0.006	-0.183	-0.205	-0.080	-0.063
	(0.092)	(0.096)	(0.200)	(0.212)	(0.035)	(0.037)	(0.133)	(0.142)	(0.129)	(0.143)
Older sib's INT skill (t-1) * Sibling bond (t)	0.012	0.013	0.175	0.179	0.004	0.004	-0.034	-0.032	0.167	0.165
	(0.153)	(0.153)	(0.392)	(0.393)	(0.062)	(0.062)	(0.261)	(0.261)	(0.222)	(0.223)
Observations	2558	2558	2475	2475	2558	2558	2475	2475	2558	2558
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note. The table presents the estimates for the translog joint technology of skill formation. The interactions between the lag of the siblings' skills and the sibling bond are instrumented by the interaction between the lag of the siblings' skills and the exogenous shifter for the sibling bond (i.e., adjustment cost to housing with a control function approach). Other controls include siblings' gender, age gap between younger and older siblings, mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, housing tenure, years lived in current address, local employment rate at the local authority where family lives, region fixed effects. Robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

A.16 Misreporting Bias

This appendix exploits teacher-reported measures of the younger sibling's socio-emotional development – rather than parental reports – to address concerns related to correlated measurement error arising from a common reporter. I use the data from the Foundation Stage Profile (FSP) questionnaire administered to teachers in Northern Ireland, Wales and Scotland and select the items that are similarly worded to the questionnaires administered to the parents. The comparable items are the following questions [Yes, No]: (i) Maintains attention and concentrates, (ii) Sustains involvement and perseveres, and (iii) Considers the consequences of words and actions.

This analysis provides a measure of the latent skill at age 5 that differs only by the nature of the respondent as similar survey questions are used across parents and teachers. Two caveats are worth noting. First, the responses to the teachers' questionnaire are unfortunately not available in disaggregated form for England. Second, similarly-worded items are available only for the externalizing skill. I therefore estimate the production function for the externalizing skill, where I use the responses reported by the teachers – instead of the parents. I consider parental investment and the sibling bond to be exogenous as estimating the investment functions would require a larger sample, which is unfortunately not available as the data are not collected from the teachers in England. Appendix Table A23 reports similar structural estimates for the self-productivity of skills and the productivity of the inputs to those obtained when using the information about the socio-emotional skills reported by the parents (Table 3 and Appendix Table A19).

Table A23: Joint technology of externalizing skill with siblings: using socio-emotional skills as reported by teachers

Outcome	**Externalizing (EXT)**
	(1)
Younger sibling's EXT skill (t-1)	0.411***
	(0.143)
Younger sibling's INT skill (t-1)	0.045
	(0.123)
Younger sibling's COG skill (t-1)	0.340***
	(0.067)
Older sibling's EXT skill (t-1)	-0.024
	(0.049)
Older sibling's INT skill (t-1)	-0.131*
	(0.070)
Sibling bond (t)	0.137***
	(0.049)
Parental investment (t)	0.038
	(0.031)
Observations	646
Other controls	Yes

Note. The table presents the estimate of the externalizing skill production function when the externalizing skill is reported by the teachers - instead of the parents. Investments are treated as exogenous. The teacher's questionnaire was administered in Northern Ireland, Wales and Scotland. The measurement system and the outcome equation are estimated jointly. Other controls include siblings' gender, age gap between younger and older siblings, mother's mental health, mother's education, mother's age, whether the household is dual-headed or single-headed, number of children, housing tenure, years lived in current address, local employment rate at the local authority where family lives, region fixed effects. Standard errors based on the GMM asymptotic variance formula in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$).

A.17 Heterogeneity: joint technology of skill formation

This appendix explores two possible sources of heterogeneity in the joint technology of skill formation: the siblings' gender and the age. Unfortunately, the exogenous shifters become weak when the sample is split and investments are allowed to be endogenous, often yielding structural estimates which are unreliable.

Appendix Tables A24, A25 and A26 present the estimates for joint skill formation technology by the older sibling's gender, younger sibling's gender and siblings' gender composition. I do not detect large differences in the estimates. Appendix Table A26 provides some suggestive evidence that the sibling bond is more productive for same-sex than mixed-sex siblings. This suggests that same-sex siblings may have more possibilities to interact, while sharing similar interests and toys. Finally, Appendix Table A27 presents the estimates for the joint skill formation technology by the siblings' age gap. The sample is split at the median age gap, which corresponds to 3 years.

Table A24: Joint technology of skill formation by older sibling's gender

Outcome	**Externalizing (EXT)**				**Internalizing (INT)**				**Cognitive (COG)**	
	Younger		**Older**		**Younger**		**Older**		**Younger**	
Older sib's gender	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Younger sib's EXT skill (t-1)	0.232	0.629***	-0.459**	-0.239**	-0.091	-0.082	-0.526*	-0.055	-0.080	-0.074
	(0.237)	(0.076)	(0.192)	(0.101)	(0.117)	(0.093)	(0.310)	(0.125)	(0.073)	(0.083)
Younger sib's INT skill (t-1)	-0.429**	-0.024	-0.208	-0.150*	0.579***	0.889***	-0.868***	-0.250**	-0.148	0.065
	(0.201)	(0.056)	(0.174)	(0.078)	(0.132)	(0.132)	(0.330)	(0.127)	(0.128)	(0.087)
Younger sib's COG skill (t-1)	0.327**	0.048	0.096	0.000	0.108	-0.208***	0.216	0.113	0.625***	0.513***
	(0.131)	(0.038)	(0.087)	(0.060)	(0.068)	(0.078)	(0.146)	(0.081)	(0.073)	(0.063)
Older sib's EXT skill (t-1)	-0.356*	-0.037	0.436***	0.674***	-0.259**	-0.228**	-0.810**	-0.285**	-0.172	-0.163*
	(0.185)	(0.049)	(0.190)	(0.086)	(0.110)	(0.111)	(0.331)	(0.110)	(0.115)	(0.097)
Older sib's INT skill (t-1)	0.028	-0.074	0.002	-0.056	0.101	-0.064	1.622***	1.313***	-0.119	-0.128
	(0.113)	(0.054)	(0.134)	(0.106)	(0.082)	(0.115)	(0.230)	(0.154)	(0.087)	(0.096)
Parental investment (t)	0.732*	0.292	0.637***	0.816*	0.105	0.573	0.869*	-0.207	0.297	0.352
	(0.433)	(0.271)	(0.338)	(0.481)	(0.229)	(0.524)	(0.514)	(0.609)	(0.258)	(0.490)
Sibling bond (t)	0.791*	0.137	0.724	0.221	0.384	0.424	1.191	0.185	0.453	0.456*
	(0.433)	(0.154)	(0.475)	(0.229)	(0.268)	(0.287)	(0.795)	(0.291)	(0.258)	(0.256)
Observations	1216	1342	1170	1305	1216	1342	1170	1305	1216	1342
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note. The table presents the estimates of the joint technology of skill formation by the older sibling's gender. Younger sibling at age 5, older sibling between age 6 and 15. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual or single headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Table A25: Joint technology of skill formation by younger sibling's gender

Outcome	**Externalizing (EXT)**				**Internalizing (INT)**				**Cognitive (COG)**	
	Younger		**Older**		**Younger**		**Older**		**Younger**	
Younger sib's gender	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Younger sib's EXT skill (t-1)	0.557***	0.226	-0.259***	-0.333**	-0.108*	-0.123	-0.177	-0.201	-0.029	-0.133
	(0.105)	(0.252)	(0.091)	(0.150)	(0.061)	(0.090)	(0.121)	(0.213)	(0.089)	(0.146)
Younger sib's INT skill (t-1)	-0.218*	-0.172	-0.176	-0.067	0.603***	0.900***	-0.779***	-0.215	0.027	-0.043
	(0.128)	(0.141)	(0.132)	(0.120)	(0.123)	(0.184)	(0.240)	(0.182)	(0.124)	(0.207)
Younger sib's COG skill (t-1)	0.091**	0.134***	0.062	-0.012	-0.045*	0.022	0.122	0.014	0.570***	0.526***
	(0.038)	(0.047)	(0.044)	(0.073)	(0.027)	(0.035)	(0.075)	(0.107)	(0.042)	(0.056)
Older sib's EXT skill (t-1)	-0.122	-0.218	0.636***	0.646***	-0.161***	-0.150*	-0.462**	-0.462**	-0.032	-0.267*
	(0.077)	(0.141)	(0.095)	(0.120)	(0.054)	(0.088)	(0.137)	(0.178)	(0.074)	(0.142)
Older sib's INT skill (t-1)	0.020	0.017	-0.110	-0.122	0.050	-0.003	1.451***	1.279***	-0.070	-0.132
	(0.067)	(0.087)	(0.096)	(0.186)	(0.049)	(0.073)	(0.174)	(0.221)	(0.069)	(0.121)
Parental investment (t)	0.227	0.646**	0.746**	0.400	0.186	0.189	0.696	0.228	0.107	0.400
	(0.337)	(0.307)	(0.345)	(0.306)	(0.222)	(0.196)	(0.456)	(0.414)	(0.346)	(0.327)
Sibling bond (t)	0.299**	0.398	0.282	0.632	0.188**	0.296	0.352	0.590	0.137	0.573*
	(0.124)	(0.339)	(0.205)	(0.431)	(0.085)	(0.206)	(0.291)	(0.624)	(0.118)	(0.335)
Observations	1312	1246	1272	1203	1312	1246	1272	1203	1312	1246
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note. The table presents the estimates of the joint technology of skill formation by the younger sibling's gender. Younger sibling at age 5, older sibling between age 6 and 15. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual or single headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

Table A26: Joint technology of skill formation by siblings' gender composition

Outcome	**Externalizing (EXT)**				**Internalizing (INT)**				**Cognitive (COG)**	
	Younger		**Older**		**Younger**		**Older**		**Younger**	
Gender composition	Mixed	Same	Mixed	Same	Mixed	Same	Mixed	Same	Mixed	Same
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Younger sib's EXT skill (t-1)	0.539***	0.497***	-0.186***	-0.719	-0.045	-0.276	-0.131	-0.363	-0.046	-0.002
	(0.078)	(0.180)	(0.051)	(0.651)	(0.063)	(0.283)	(0.102)	(0.440)	(0.063)	(0.157)
Younger sib's INT skill (t-1)	-0.251	-0.141	0.031	-0.032	0.663***	0.872***	-0.755**	-0.449*	-0.043	0.051
	(0.204)	(0.087)	(0.128)	(0.127)	(0.199)	(0.190)	(0.309)	(0.265)	(0.210)	(0.097)
Younger sib's COG skill (t-1)	0.097	0.149**	0.131**	0.042	0.011	-0.071	0.176	0.096	0.548***	0.588***
	(0.098)	(0.041)	(0.065)	(0.115)	(0.106)	(0.072)	(0.132)	(0.095)	(0.100)	(0.046)
Older sib's EXT skill (t-1)	-0.159***	-0.154	0.683***	0.198	-0.257***	-0.412	-0.460***	-0.664	-0.143*	-0.103
	(0.053)	(0.166)	(0.060)	(0.673)	(0.079)	(0.287)	(0.113)	(0.477)	(0.075)	(0.158)
Older sib's INT skill (t-1)	-0.018	-0.012	0.031	-0.032	-0.056	0.053	1.648***	1.302***	-0.209	-0.044
	(0.156)	(0.044)	(0.128)	(0.127)	(0.171)	(0.090)	(0.257)	(0.145)	(0.173)	(0.049)
Parental investment (t)	0.625	0.363	0.464	1.238	-0.052	0.556	0.907	0.543	0.467	0.108
	(0.502)	(0.273)	(0.391)	(1.251)	(0.549)	(0.519)	(0.693)	(0.843)	(0.576)	(0.298)
Sibling bond (t)	0.298	0.342	0.106	1.293	0.531	0.815	0.039	0.825	0.449	0.243
	(0.358)	(0.318)	(0.272)	(1.325)	(0.399)	(0.592)	(0.544)	(0.900)	(0.411)	(0.319)
Observations	1266	1292	1222	1253	1266	1292	1222	1253	1266	1292
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note. The table presents the estimates of the joint technology of skill formation by siblings' gender composition. Younger sibling at age 5, older sibling between age 6 and 15. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual or single headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

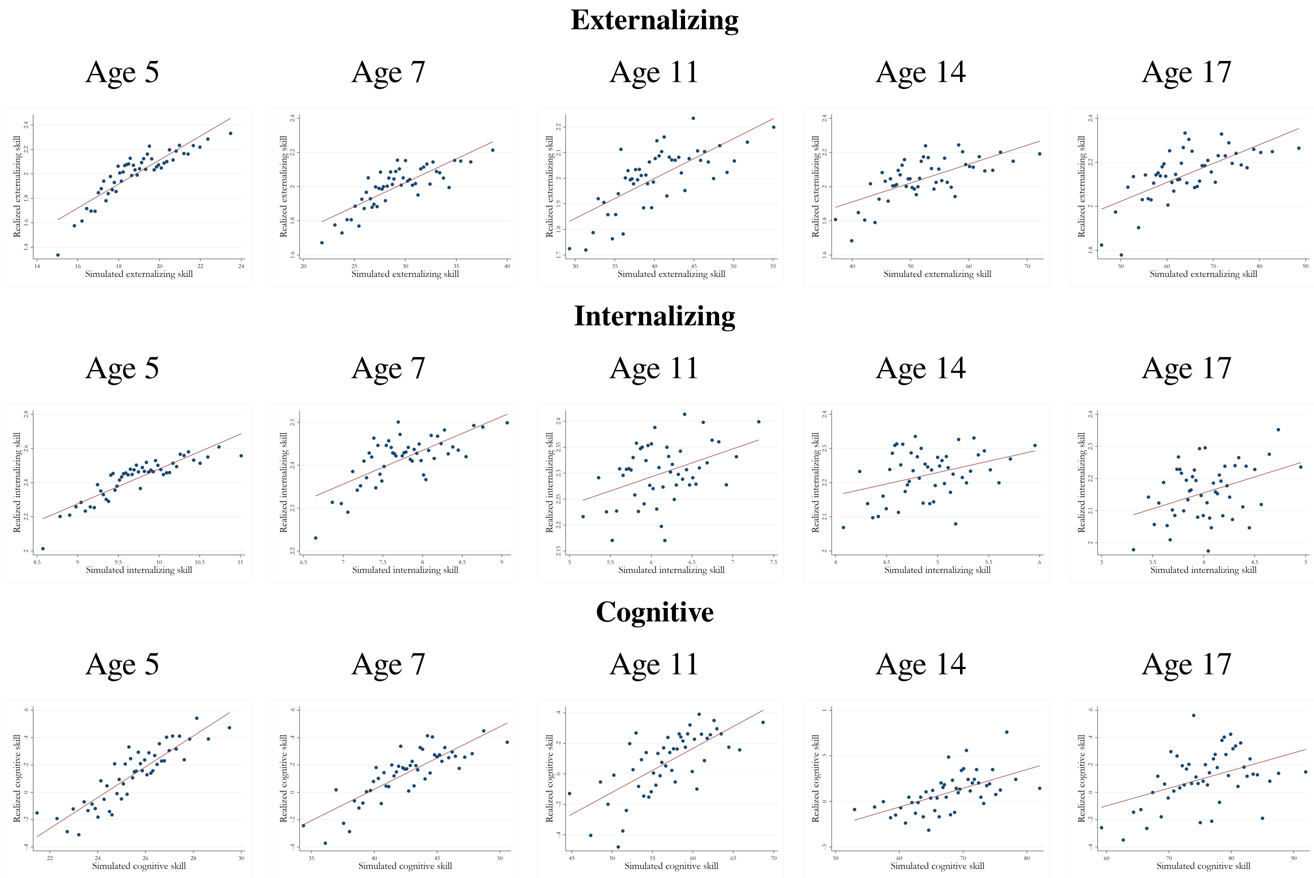
Table A27: Joint technology of skill formation by siblings' age gap

Outcome	**Externalizing (EXT)**				**Internalizing (INT)**				**Cognitive (COG)**	
	Younger		**Older**		**Younger**		**Older**		**Younger**	
Age gap	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Younger sib's EXT skill (t-1)	0.476***	0.605***	-0.240***	-0.281**	-0.110	-0.146	-0.230**	-0.072	-0.125	-0.017
	(0.101)	(0.103)	(0.068)	(0.108)	(0.077)	(0.137)	(0.112)	(0.121)	(0.102)	(0.085)
Younger sib's INT skill (t-1)	-0.145*	-0.217*	-0.149**	-0.177	0.824***	0.902***	-0.505***	-0.240	-0.067	-0.046
	(0.086)	(0.116)	(0.071)	(0.134)	(0.114)	(0.183)	(0.150)	(0.172)	(0.101)	(0.129)
Younger sib's COG skill (t-1)	0.160***	0.054	0.040	0.056	-0.039	-0.064	0.124*	0.040	0.592***	0.593***
	(0.034)	(0.046)	(0.033)	(0.048)	(0.037)	(0.063)	(0.066)	(0.062)	(0.044)	(0.054)
Older sib's EXT skill (t-1)	-0.185**	-0.073	0.676***	0.573***	-0.163*	-0.289***	-0.338**	-0.379***	-0.225*	-0.123
	(0.083)	(0.067)	(0.094)	(0.081)	(0.092)	(0.098)	(0.153)	(0.099)	(0.116)	(0.080)
Older sib's INT skill (t-1)	0.029	-0.124*	0.064	-0.163*	0.019	0.010	1.410***	1.126***	-0.069	-0.100
	(0.071)	(0.067)	(0.065)	(0.099)	(0.068)	(0.112)	(0.149)	(0.146)	(0.085)	(0.074)
Parental investment (t)	0.456*	0.376	0.509**	0.608*	0.350	-0.095	0.396	0.371	0.407	0.335
	(0.264)	(0.277)	(0.235)	(0.321)	(0.265)	(0.404)	(0.383)	(0.356)	(321)	(0.331)
Sibling bond (t)	0.269*	0.473*	0.317*	0.375	0.283	0.779**	0.493	0.208	0.516**	0.184
	(0.161)	(0.278)	(0.183)	(0.296)	(0.182)	(0.390)	(0.303)	(0.338)	(0.216)	(0.288)
Observations	1573	985	1531	994	1573	985	1531	994	1573	985
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note. The table presents the estimates of the joint technology of skill formation by siblings' age gap. Younger sibling at age 5, older sibling between age 6 and 15. Small age gap corresponds to siblings with an age gap below or equal to 3 years old (median age gap), age gap corresponds to siblings with an age gap above 3 years old. Measurement system and equations are estimated jointly (Muthén, 1984). Other controls include siblings' gender, age gap between younger and older sibling, mother's mental health, mother's education, mother's age, whether the household is dual or single headed, number of children, housing tenure, years lived in current address, local employment at the local authority where family lives, region fixed effects. Source: University of London. Institute of Education. Centre for Longitudinal Studies. (2017). Millennium Cohort Study: Geographical Identifiers, Third Survey: Secure Access. [data collection]. 2nd Edition. UK Data Service. SN: 7760, http://doi.org/10.5255/UKDA-SN-7760-2. Standard errors based on the GMM asymptotic variance formula in parentheses (*** p<0.01, ** p<0.05, * p<0.1).

A.18 Validating the structural estimates

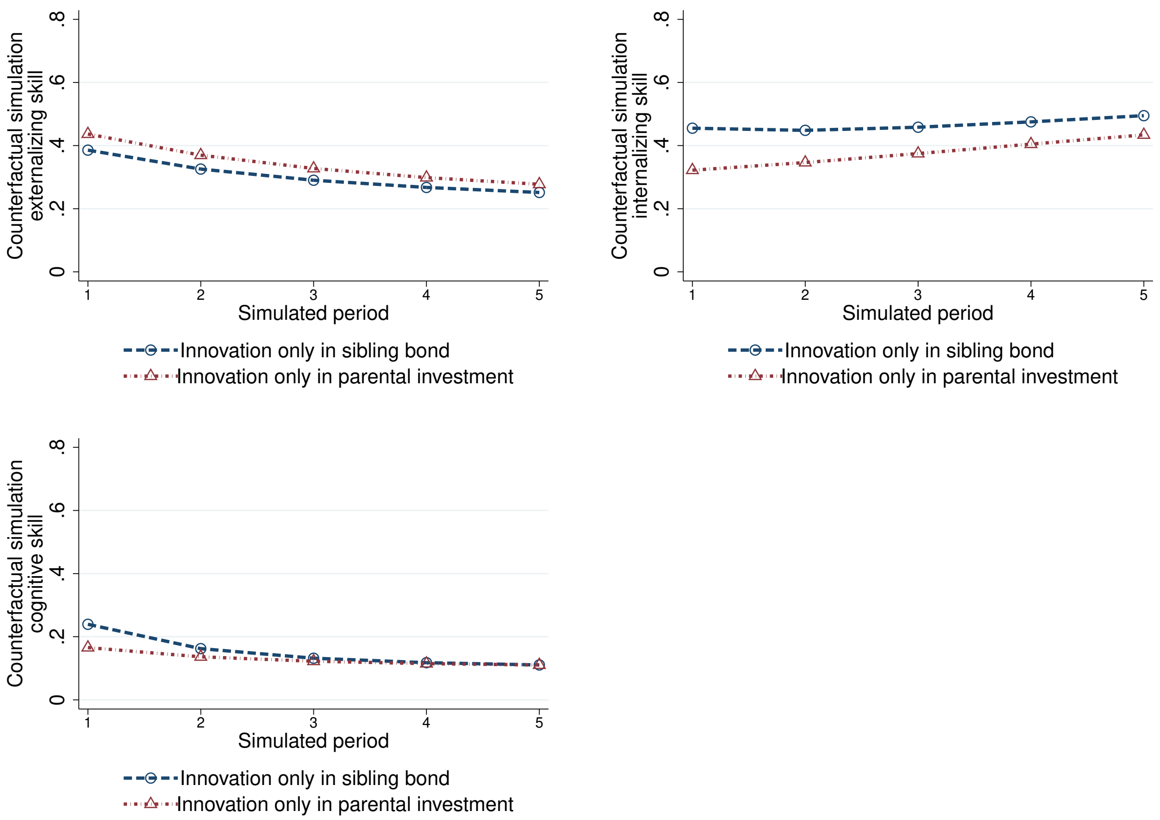
Figure A6: Validation exercise: future realized development and *simulated* development, as implied by the structural estimates of the joint skill formation technology.



Note. The figures present the binscatter plot of the association between the future realized development (y-axis) and the simulated development (x-axis), as implied by the structural estimates of the technology of skill formation, for the younger sibling at ages 5, 7, 11, 14 and 17. The unit of the y-axis is in standard deviation units. Three dimensions of development are considered: externalizing (ability to engage in interpersonal activities), internalizing (ability to focus and pursue long-term goals) and cognitive skills (ability to complete tasks and learn).

A.19 Counterfactual simulations

Figure A7: Counterfactual simulations of hypothetical interventions



Note. The figures present illustrative model-based simulations of exogenous increases in either sibling bond or parental investment by 1 standard deviation over simulated periods 1-5 (ages 5, 7, 11, 14, and 17), as implied by the estimated joint technology of skill formation. The parameters are assumed to remain constant across all simulated periods.