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Cognitive spillover benefits of early childhood education: Quasi-experimental evidence based on random class assignment from China

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ABSTRACT

This paper investigates the cognitive spillover effects of classmates' early childhood education (ECE) experience on junior high school students, using data from the first two waves of the China Education Panel Survey (CEPS). To address potential endogeneity in classmates' composition, we leverage exogenous variation in students' ECE experience generated by random class assignment upon their entry into junior high school. Employing a value-added model, we find that classmates' ECE experience significantly enhances students' cognitive performance. Specifically, a 10-percentage-point (pp) increase in classmates' ECE enrollment raises students' cognitive scores by 0.08 standard deviations (SD), while an additional year of classmates' ECE experience shows insignificant effect. As to underlying mechanisms, the spillover effects are driven by an improved class environment, increased parental homework support, stronger learning efforts and enhanced non-cognitive skills of students, together with the peer interactions within social networks. Among them, students' behaviors exert the strongest explanatory power of 13 %. Furthermore, the benefits are more pronounced among urban students with ECE experience, those from better-educated families and with moderately below-average baseline cognitive skills.

1. Introduction

Although substantial research highlights the private benefits of early childhood education (ECE),[1] the prevalence of ECE globally has stagnated for a long time. The latest statistics indicate that in 2022, three out of 10 children worldwide lacked access to at least one year of organized ECE, a rate unchanged since 2015 (The United Nations, 2024). COVID-19 further caused a 1.5 percentage points (pp) decline in global ECE enrolment rates (The United Nations, 2024). Additionally, many children lack full-time access to ECE during their preschool years.[2] One underlying reason might be that many countries have yet to fully appreciate the societal returns of ECE, leading to inadequate public investment. To date, only a quarter of countries have made ECE compulsory, and only half of them offer it for free (The United Nations, 2024). To achieve the SDG target of universal access to quality early childhood development, care and preprimary education by 2030 (WHO, 2017), it is urgent to understand more about the social benefits of ECE, rather than only its private benefits.

This study aims to deepen understanding of the social returns to ECE by examining the cognitive spillover effects of classmates' ECE

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[1] Many previous studies have shown the private human capital benefits of ECE, including benefits on skill development, improvements of behaviors and so on, whether in developing countries (Arapa et al., 2021; Berlinski et al., 2008, 2009; Bietenbeck et al., 2019; Brinkman et al., 2017; Gong et al., 2016) and developed countries (Blanden et al., 2016; Duncan et al., 2022; Heckman et al., 2013; Gray-Lobe et al., 2023).

[2] Among those with ECE experience in Cambodia and Mongolia, 90 % attended for no more than one year (Rao et al., 2019). Even in the United States, only 34 % of four-year-olds children were able to attend state-funded ECE institutions in 2019 (Gray-Lobe et al., 2023).

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experience in China.[3] We find that omitting these effects leads to underestimation of ECE's cognitive benefits. To be specific, we use data from the China Education Panel Survey (CEPS), a large-scale nationally representative survey, which includes 19,487 junior high school students, their parents, teachers, and principals from 112 schools in 28 counties in China. Our analyses utilize longitudinal records of students entering junior high school from 2013 to 2014 (Grade 7) to 2014–2015 (Grade 8) academic years and focus on classrooms with a stable composition between Grades 7 and 8, following initial random assignment upon entrance. This design enables us to analyze the spillover effects of classmates' ECE experience in Grade 7 on students' cognitive gains in Grade 8 within a value-added framework, exploring mechanisms across various dimensions, including classroom dynamics, parental and student behaviors, among others.

We employ a quasi-experimental design involving random classroom assignment and control for a range of covariates to address potential endogeneity in peer composition. First, the identification of effects of classmates' ECE experience may be influenced by factors such as parents' selective school choice or principals' selective teacher assignment. To address this, we incorporate school fixed effects to capture within-school variation and include a set of characteristics of head teachers as covariates. Another potential concern stems from endogenous sorting of students across classes within the same schools. To mitigate this, we rely on random class assignments in part of sample schools to ensure the exogeneity of peer composition. This enables the identification of causal effects by comparing students within the same school and with similar characteristics, with the sole difference being classmates' ECE composition due to random assignment. We further validate this approach through four tests: examining the correlation between classmates' ECE composition and students' cognitive ability in Grade 7, conducting a balance test of educational resources across classes, verifying the adequacy of within-school variation in classmates' ECE composition, and performing a placebo test by randomly reallocating the sampled students from the 52 sample schools to two different classes.

Our results demonstrate that classmates' ECE experience significantly benefits students' cognitive performance. Specifically, a ten-percentage-point (pp) increase in classmates' ECE enrollment rate raises students' cognitive scores by 0.08 standard deviations (SD), although classmates' ECE duration shows insignificant effect. That said, increasing classmates' ECE enrollment rate from the current 85–100 % accounts for 80–85 % of the private cognitive benefits of ECE experience. Moreover, we find that cognitive spillover effects of ECE are driven by an improved class environment, more parental involvement, enhanced learning efforts and non-cognitive skills of students, together with interactions within social networks. Among them, students' behaviors exert the strongest explanatory power (13 %), followed by classroom dynamics (10 %), and parental engagement (6 %). Heterogeneous analyses show that students with ECE experience and better educated parents benefit more from classmates' ECE experience. Finally, quantile estimates indicate that students with moderate below-average performance gain the most from classmates' ECE experience.

This study enriches the literature in the following three ways. First, it extends the limited body of research on ECE spillover effects, deepening our understanding of the social returns to ECE investment. Prior studies, such as Garces et al. (2002), first identified intrafamily spillover effects of the Head Start program, particularly in reducing crime. However, existing evidence on the external benefits of ECE attendance primarily stems from developed economies like the United States (e.g., Ladd et al., 2014; Dodge et al., 2017; Williams, 2019; Neidell and Waldfogel, 2010). Identifying these impacts is especially crucial for developing countries, where limited educational resources need efficient distribution. This study contributes to this field through four dimensions: 1) providing reliable causal evidence of ECE spillover effects in the context of developing countries,[4] 2) examining the spillovers of ECE across entire classrooms, which are recognized as crucial on students' performance (Carman and Zhang, 2012; Ding and Lehrer, 2007; Lu and Anderson, 2015), 3) exploring the under-studied dosage effects of ECE (Behrman et al., 2004) to provide a more precise analysis compared with Zhang et al. (2023), and 4) being among the first to examine the nonlinear impacts of peers' ECE experiences on adolescents with varying cognitive abilities.

In further, this paper contributes through providing one of the most comprehensive causal evidence on the impact of classmates' ECE experience on adolescents' cognitive abilities. Unlike previous studies predominantly reporting correlational relationships between peers' ECE attendance and children's performance (e.g., Garces et al., 2002; Ladd et al., 2014; Dodge et al., 2017; Neidell and Waldfogel, 2010; Wang, 2021), this study leverages the random assignment of students to middle school classes, enabling identification of causal effects at the class level. While Zhang et al. (2023) also used random assignment, they did not employ a value-added model to control for students' baseline performance or exclude students reassigned between Grades 7 and 8, both of which limited causal interpretation. Our approach addresses these gaps by applying stricter sample restrictions and a value-added framework, strengthening the causal identification of our results.

Second, this study enriches the literature on peer effects in Chinese settings and highlights an underexplored dimension, the long-term spillovers of peers' ECE opportunities. Recent work has advanced our understanding of peer effects in China across multiple domains: academic achievement (Wu et al., 2023; Huang and Zhu, 2020), gender composition (Lu and Anderson, 2015; Gong et al., 2018; Lao, 2023; Luo and Yang, 2023), and shadow education participation (Xi and Li, 2020; Pan et al., 2022; Guo and Qu, 2022; Li and Lin, 2023), extending to non-cognitive domains like prosocial behavior (Deng et al., 2024) and health (Luo and Pan, 2020), with additional evidence on how school environments moderate these effects (Wang et al., 2021). Yet, most studies focus on contemporaneous peer traits, with limited attention to how historical educational disparities shape peer dynamics (Opper, 2019). By examining how peers' disparities in ECE access and dosage affect adolescent cognition, this study advances the literature through highlighting the social returns to equity in early educational opportunities. Finally, this paper explores the potential working channels of ECE, including classroom environment, the behaviors of teachers, parents, and students, improvements in students' non-cognitive skills, and peer interactions within social networks. These extensive analyses enhance our understanding of why classmates' ECE experience is impactful during adolescence. To our knowledge, we provide one of the first evidence to demonstrate how peers' ECE experiences influence students' externalizing and internalizing behaviors, both of which significantly relate to cognitive improvement. Furthermore, we present

[3] There are three main reasons why we focus on cognitive ability as the primary outcome variable. First, evidence from neuroscience, behavioral science, and economics suggests that cognitive skills tend to stabilize earlier than non-cognitive and socio-emotional skills, typically around the age of 10 (Heckman et al., 2013; Knudsen et al., 2006). This implies that early education plays an irreplaceable role in shaping cognitive skills, a role that is difficult to compensate for later. Second, standardized cognitive ability tests provide a relatively objective measure of cognitive skills, less influenced by external factors (such as personal study motivation) or subjective biases than test scores, making them less susceptible to be manipulated (Kautz et al., 2014). Third, cognitive ability has profound predicting role on employment, wages, and long-term labor market outcomes (Kautz et al., 2014).

[4] Although Wang (2021) and Zhang et al. (2023) made initial attempts to examine the externalities of peers' ECE experiences in China, their studies did not incorporate a sufficiently random class assignment quasi-experimental design or establish a necessary value-added model. Consequently, their estimates are limited in providing a credible causal interpretation. In the following section, we will discuss these shortages in depth.

a novel perspective by extending the analysis of ECE peer effects from the classroom level to the sub-classroom level, providing one of the first evidence that the observed spillover effects of ECE are primarily driven by peers with ECE experience within homogeneous sub-groups.

The rest of our study is structured as follows. 2 introduces the background of ECE policies in China. 3 presents the conceptual framework. 4 describes the sample and data. 5 describes the empirical framework used by us. 6 presents our empirical findings. The final section concludes.

2. Background

In China, ECE serves children aged 3–6 and is divided into two main types: preschool and kindergarten. Preschools, the predominant form of ECE, typically offer early care and education for no more than three years (Rao et al., 2017). In contrast, kindergartens, often affiliated with primary schools, offer one- to two-year programs preparing children for first grade (Rao et al., 2017). Kindergartens once dominated rural ECE provision, while in urban areas, formal preschools, including both public and private institutions, have dominated the ECE market (Tang et al., 2023). These two types of ECE differ in their historical development and pedagogical approaches. Preschools in China have existed since the early 1950s and are distributed in both urban and rural settings, while kindergartens emerged later, gaining support from the State Education Commission in 1983, especially in rural areas (Tian et al., 2020). Furthermore, rural preschools often emphasize play-based learning, whereas kindergartens generally focus on subject-specific instruction for 5- to 6-year-olds (Rao et al., 2017).

For a long time, the prevalence of ECE in China had been relatively limited. The central government had played a limited role in ECE provision, with primary providers being rural village committees, state-owned enterprises in urban areas, and private ECE providers (Tian et al., 2020). From the late 1990s to early 2000s, the number of ECE institutions in China declined significantly due to the wave of bankruptcies among state-owned enterprises, the deterioration of rural collective organizations, along with cuts in public funding for preschool education (Tian et al., 2020; Su et al., 2020). By 2009, the gross enrollment rate of ECE was just 51 %, far from universal access (Fig. 1). During this period, kindergartens also played an important role in ECE provision. By 2008, kindergarten enrollment in rural China accounted for 52 % of total ECE enrollment (Wu et al., 2012). However, many children still lacked access to any form of ECE (Wu et al., 2012).

Since 2010, the Chinese government has increasingly emphasized the significance of preschool education for child development, resulting in considerable investment in early childhood education. In 2010, China established new goals and visions for the advancement of ECE (State Council, 2010a). The primary goal is to achieve universal ECE access, targeting enrollment rates of 95 % for children aged 5–6, 80 % for those aged 4–6, and 70 % for children aged 3–6 by 2020. Meanwhile, the central government has intensified financial support for ECE, especially in regions with limited access, such as the western and rural areas, and provided subsidies for low-fee private preschools (State Council, 2010b). As a result, public funding for preschool education surged from US$3.5 billion in 2009 to US$47.8 billion in 2017.[5] The enrollment rate of ECE also rose rapidly, from 57 % in 2010 to 83 % in 2019 (Fig. 1).

While China has made substantial progress in ECE expansion, meaningful disparities persist between urban and rural children in its access, duration, and quality.

Access Among students surveyed in CEPS, urban Grade7 (Grade9) students' ECE enrollment reached 86 % (85 %) compared to 77 % (74 %) for rural children, a 9–11 percentage-point gap reflecting improved but uneven coverage (Fig. 2A). Accelerated preschool construction since 2010 has increased rural supply, though geographic disparities persist as new centers were predominantly built in township seats rather than remote villages (Chen et al., 2023).

2.1. Duration

Not all children in China complete three full years of ECE. CEPS data shows that urban Grade7 (Grade 9) students have 2.38 (2.23) years of ECE exposure on average, compared to 1.84 (1.63) years for their rural peers, reaching a 0.5–0.6 year gap (Fig. 2B). This gap primarily reflects delayed enrollment, with China Family Panel Studies (CFPS) data showing 29 % of children not enrolled in preschool at age 4 (Su et al., 2020). Specifically, rural children aged 3–4 years old exhibit enrollment rates that are 10–20 percentage points lower than their urban counterparts (Chen et al., 2023).

2.2. Teacher quantity

Children-teacher ratio in rural areas averaged 26:1 versus 14:1 in urban areas in 2018 (Fig. 3A), despite significant recent improvements in rural regions.

2.3. Teacher qualifications

Rural ECE teachers are less experienced and less likely to receive high-quality training compared to urban peers (Rao et al., 2017). Even in economically developed Zhejiang province, Hu et al. (2014) found that nearly all rural private preschool teachers held less than associate college degrees.

2.4. Resource allocation

While rural per-child ECE expenditures increased over 300 % from 2011 to 2018, they reached only 70 % of the national average by 2018 (Fig. 3B), explaining persistent gaps in preschool facilities and materials between urban and rural areas (Wong et al., 2013; Li et al., 2016). Some rural preschools even lacked essential health and safety provisions (Hu et al., 2014).

Given the disparities in access to and intensity of ECE, combined with the interactive classroom environment in Chinese junior high schools, the following research questions naturally arise:

1. Does ECE exhibit cognitive spillover effects? In other words, how do classmates' ECE attendance and duration influence cognitive abilities of junior high school students?
2. What are the underlying mechanisms through which classmates' ECE experience affects students' cognitive performance?
3. Do these effects vary across subgroups, such as urban and rural students?

3. Conceptual framework

The theoretical foundation of this study builds on the human capital formation framework developed by Cunha et al. (2010), which conceptualizes cognitive skills as dynamic outcomes produced through cumulative inputs at earlier stages. We model cognitive ability (c) as the key component of human capital stock (θ^c). Following the literature (Cunha et al., 2010; Heckman et al., 2013; Kinsler and Pavan, 2020; Golsteyn et al., 2021; Guo and Qu, 2022), the evolution of human capital depends on multiple inputs: prior cognitive stock (H_t), classroom environment (R_t), parental investments (P_t), individual personalities (M_t) including learning efforts and non-cognitive traits, and random shocks (e_t). $Z_t$includes a series of personal-level demographic and classroom-level characteristics. The relationship is captured by the Eq. (1):

[5] Source: http://www.moe.gov.cn/jyb_xwfb/moe_1946/fj_2017/201705/t20170503_303596.html; http://www.moe.gov.cn/jyb_xwfb/gzdt_gzdt/s5987/202104/t20210427_528812.html.

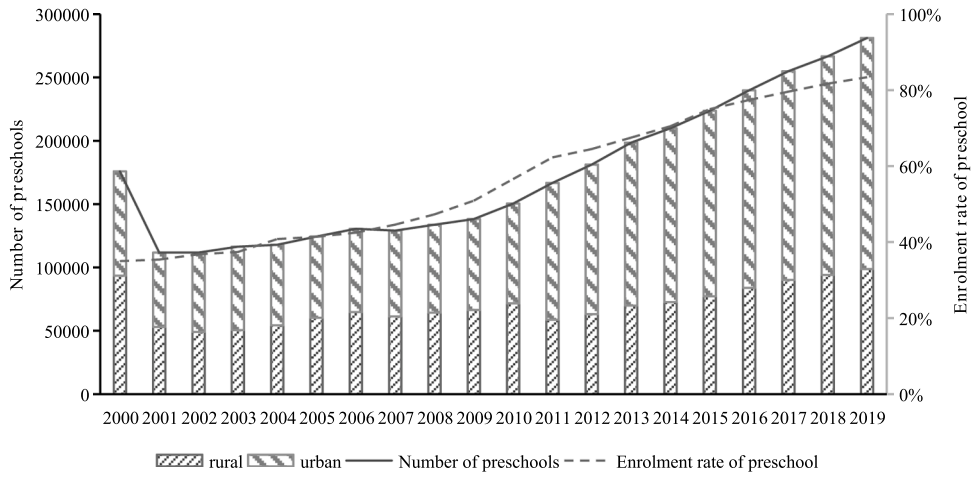

Fig. 1. Numbers of preschools and preschool enrollment rate from 2000 to 2019 in China.
Source: Educational Statistics Yearbook of China (2000–2019).

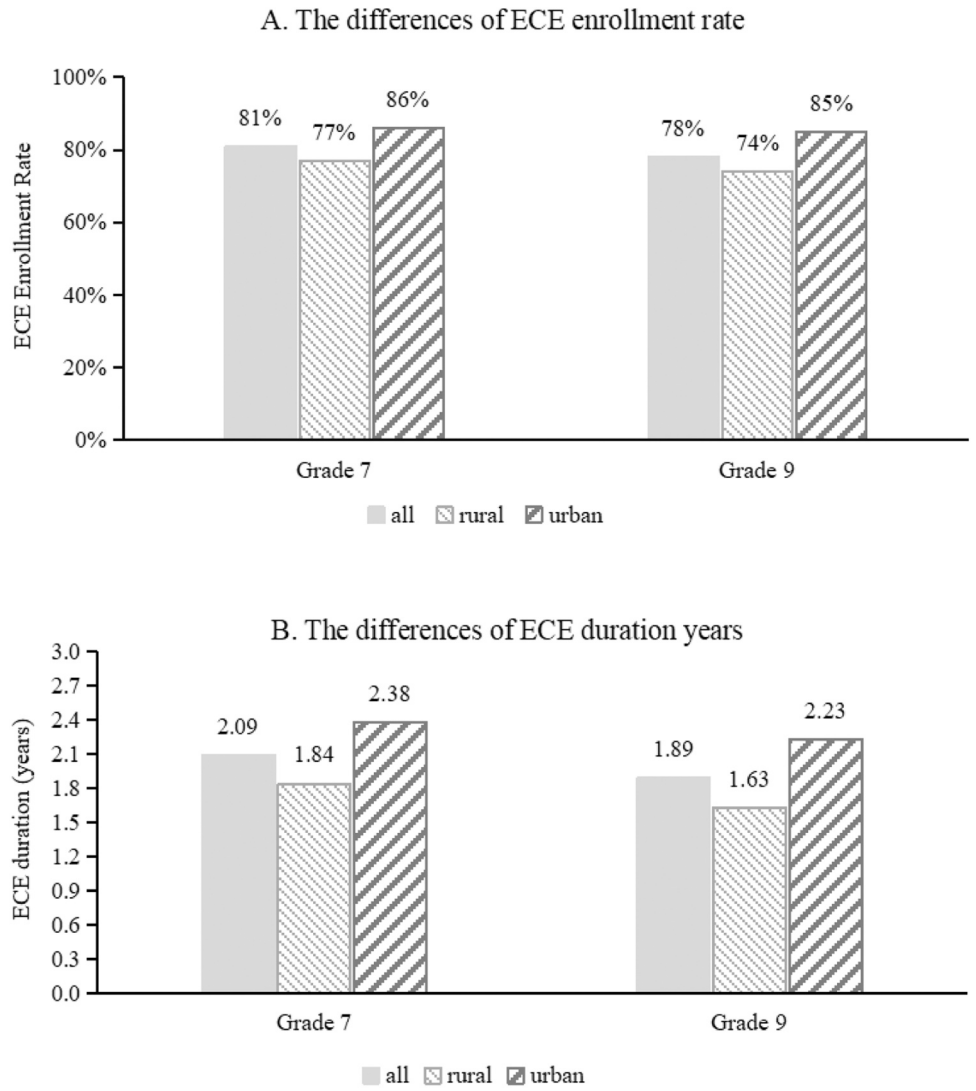

Fig. 2. Urban-rural differences in preschool educational attendance.
Source: 2013 CEPS.

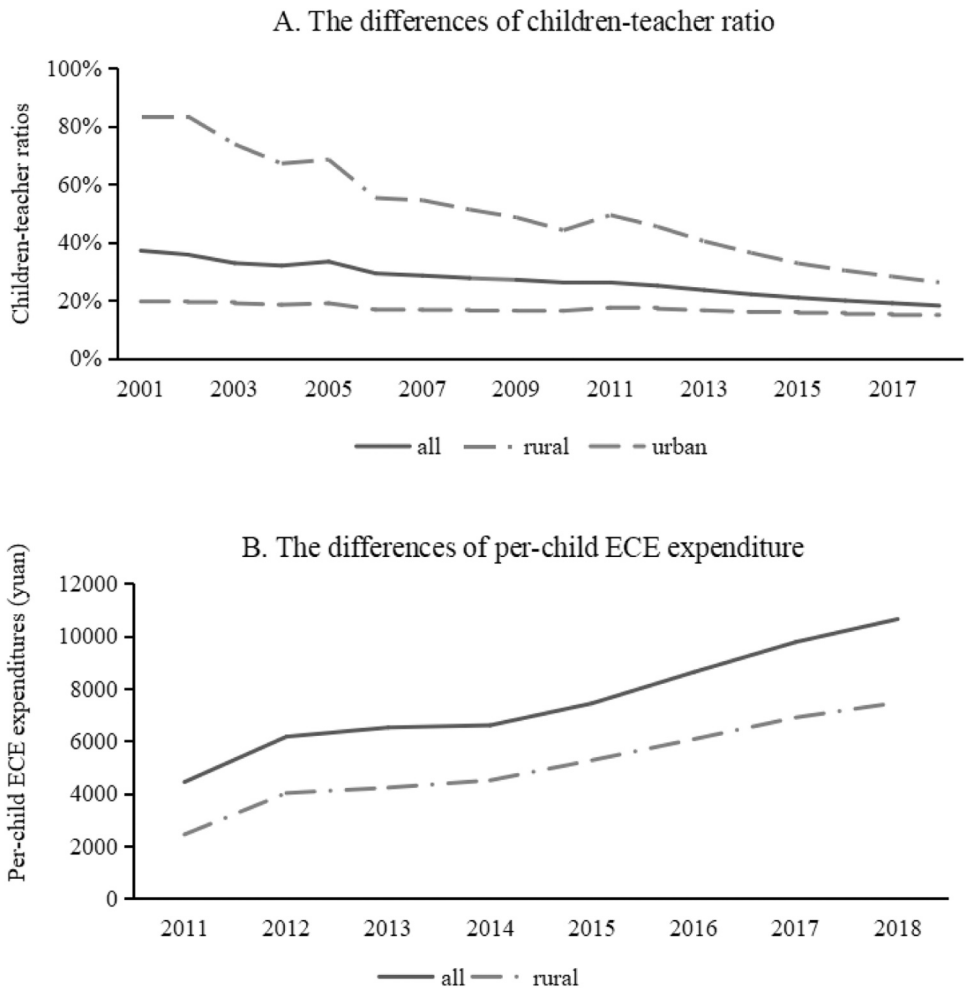

Fig. 3. Urban–rural differences in preschool educational quality.
Source: Educational Statistics Yearbook of China (2001–2018) and China Educational Finance Statistical Yearbook (2011–2018).

$$\theta^{c}_{t+1} = g^{c}_{t}(H_t, Z_t, R_t, P_t, M_t, e_t) \quad (1)$$

In our study context, t corresponds to 7th grade when students are randomly assigned to classes, while t + 1 corresponds to the time of cognitive ability testing in 8th grade.

Classmates' ECE exposure may initially influence cognitive development through external factors ($R_t$andP_t). The primary channel operates via classroom dynamics: when a critical mass of students possesses ECE experience, it cultivates more conducive learning environments. This occurs through two distinct pathways. First, improved peer behaviors allow teachers to reallocate time from classroom management to instructional quality enhancement, as demonstrated by Neidell and Waldfogel (2010) and Opper (2019). Another potential channel is that classmates with better performance can be observed by their parents, thus leading to the competition in parental education investments (Guo and Qu, 2022; Kinsler and Pavan, 2020).

ECE experience of classmates may also shape students' cognitive development through individual-level factors (M_t), including both stable traits and observable behaviors. Exposure to ECE-experienced peers can improve students' non-cognitive skills, such as reducing behavioral problems, which has been a well-documented benefit of ECE (Heckman et al., 2013). These non-cognitive skills, in turn, positively predict individual cognitive performance (Golsteyn et al., 2021). Additionally, peers with ECE experience may serve as role models, encouraging better study habits and classroom engagement, which has been supported by Zhang et al. (2023).

To conclude, we illustrate the causal chain through which classmates' ECE experience generates spillover effects via a two-stage process (Fig. 4). In the first stage, based on the social network theory (Wu et al., 2023), these effects might emerge through peer interactions in social networks. Close connections between peers lead to changes in classroom environments, family behaviors, and individual actions. In the second stage, consistent with the skill formation theory (Cunha et al., 2010), these modified environmental conditions, augmented human capital investments, together with enhanced non-cognitive skills would collectively support cognitive skill development.[6] Moreover, consistent with the dynamic complementarity in skill formation theory (Cunha et al., 2010), disadvantaged groups tend to derive more marginal benefits from ECE. Consequently, students from disadvantaged backgrounds may experience disproportionately larger gains from classmates' ECE experience.

The abovementioned conceptual framework naturally leads to three testable research hypotheses:

H1. Classmates' ECE experience positively affects students' cognitive abilities.

[6] While Fig. 4 simplifies by not showing how family/environment factors directly affect individual effort, our analysis carefully controls for this. To be specific, we separate out the channels of individual efforts and personalities, and measure relative explanatory power of each mechanism in 6.2. We also conduct robustness checks for potential confounding factors, including the inclusion of other peer-level controls (e.g., classroom gender composition) in 6.4.

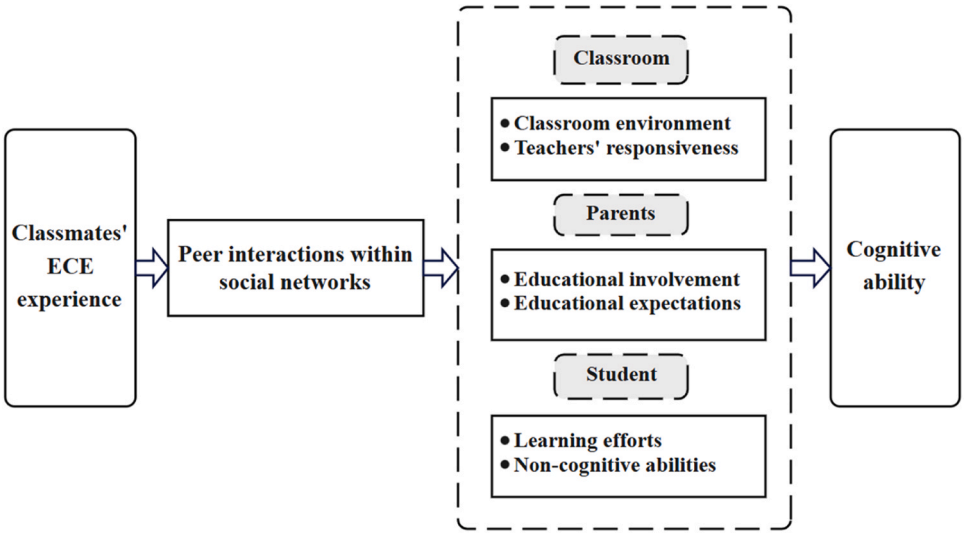

Fig. 4. The causal chain of spillover effects of classmates' ECE experience.

H2. These spillover effects work through (a) improved classroom environments, (b) increased parental investments, and (c) enhanced learning efforts and non-cognitive skills.

H3. The cognitive spillover effects of classmates' ECE experience are heterogeneous, with more benefits for students from disadvantaged backgrounds, such as those from rural areas.

4. Data, sample, and variables

4.1. Data

Our analyses are based on data from CEPS, a comprehensive and representative survey covering junior high school students in Grades 7–9 across China, organized by Renmin University of China. For the 2013–2014 academic year, CEPS applied a multi-stage sampling approach guided by Probability-Proportional-to-Size principles. Initially, stratification was carried out using administrative divisions and socioeconomic variables, such as local average schooling years and the migration rate, to select 28 counties. Within each selected county, additional stratification, based on school enrollment size and type, allowed the selection of four junior high schools. Ultimately, 112 schools across these counties were chosen, from which a total of 438 classes (two each of Grade 7 and Grade 9, except in ten schools with only one class per grade) were sampled. Altogether, 19,487 students were involved in the baseline survey conducted during the 2013–2014 academic year. Our study uses data from the first two waves of CEPS (the 2013–2014 and 2014–2015 academic year).[7]

4.2. Class assignment and study sample

To construct the subsample suitable for quasi-experimental analysis, we adopted a four-step selection process inspired by Gong et al. (2021) and Guo et al. (2022). As shown in Fig. 5, we first excluded three schools that had only a single Grade 7 class, as within-school variability in peer composition was necessary for our analyses. This yielded 109 schools, each with two Grade 7 classes. We then focused on 90 schools where principals reported that new Grade 7 students were randomly allocated to classes. Additionally, responses from homeroom teachers confirmed that in some schools, students were assigned to classes not based on academic performance, leaving 57 schools for us where both principal and teacher reported the random class assignment.

To ensure the stability in class composition, we verified whether sample students in the 57 schools remained in the same classes from Grade 7 to Grade 8. We excluded five schools that reorganized classes between waves, indicating reassignment. Additionally, we excluded students reported a preschool starting age later than primary school starting age. As a result, our final study sample comprises 52 schools, 104 classes and 4220 students with complete information on their ECE experience.

4.3. Variables

Across both survey waves, a series of questionnaires were distributed to the sampled students, parents, subject and homeroom teachers and principals. For this study, we mainly use data from three specific modules in each wave.

4.3.1. Classmates' ECE experience

We measure classmates' ECE experience using both their ECE enrollment rate and their average duration enrolled in ECE. First, we measure classmates' ECE enrollment rate by the responses to the question "Have you ever gone to a preschool/kindergarten since your three years old?" The ECE experience of a single student equals one if he/she answers "yes" and equals zero otherwise. Accordingly, we calculated classmates' ECE enrollment rate at the class level, excluding the sample students themselves. The other is classmates' average ECE duration, where we impute the duration of a single student by subtracting his/her age at preschool/kindergarten entry from the age at primary school entry.

4.3.2. Cognitive skills of students

We measure students' cognitive skills drawing on the cognitive ability test from CEPS.[8] To be specific, the CEPS developed and implemented an independent cognitive test for surveyed students according to the three-parameter logistic item response theory (IRT). The test evaluates students' aptitude in reasoning and problem-solving through three dimensions: verbal, nonverbal (including both visual and spatial skills), and arithmetic and logic. The first wave includes 20 questions, while the

[7] It is notable that data from the third and fourth waves are not publicly available. Also, the 9th graders were not surveyed since the second waves due to their graduation. In this case, our study draws on the data on the 7th graders surveyed in 2013–2014 and 2014–2015 academic year.

[8] Source: http://ceps.ruc.edu.cn/xmwd/dcsc.htm.

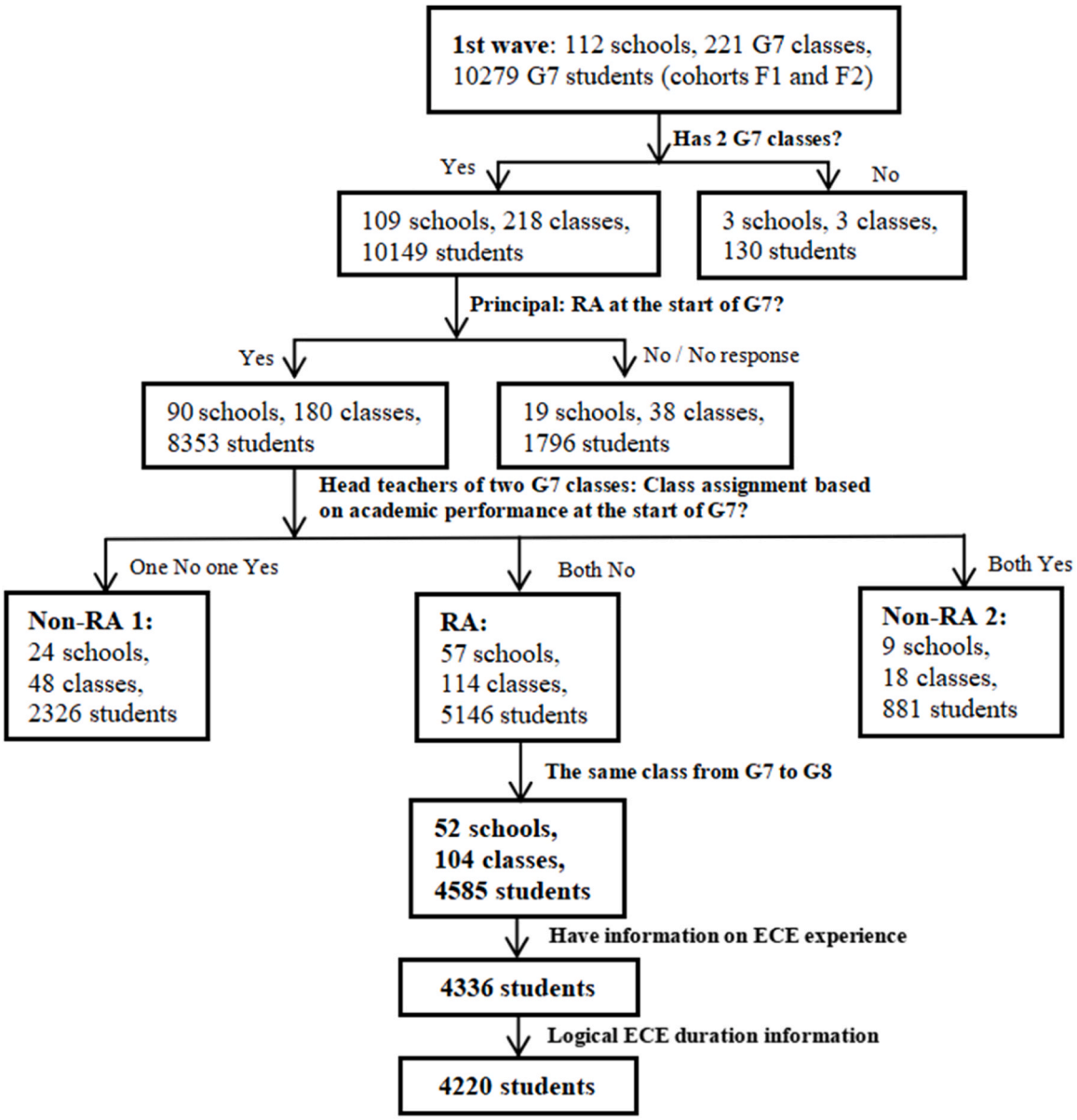

Fig. 5. Study sample construction procedure. ***Note:*** G7 stands for Grade 7, RA stands for random assignment.

second wave expands to 35 questions. Each question is scored with one point for a correct response and zero for an incorrect response. The raw score tends to be the sum of the scores of all questions, thus ranging between 0 and 20 and between 0 and 35 in the first and second wave, respectively. We standardized the raw scores to construct the measure of cognitive skills mainly used in this paper.

4.3.3. Covariates

Following relevant literature (Carman and Zhang, 2012; Ding and Lehrer, 2007; Neidell and Waldfogel, 2010; Gong et al., 2021), we controlled for multiple variables at different levels. At the student level, the covariates included age, gender, ethnicity, number of siblings, boarding status, and personal ECE experience. Household-level covariates included parental education, marital status, migration status of parents, Hukou status, and four dummy variables representing household socioeconomic status (SES) categories, using "very poor" as the reference. At the class level, we controlled for class size and homeroom teacher characteristics, including age, gender, educational background, and teaching experience.

4.3.4. Mechanism variables

Following the literature (Cunha et al., 2010; Heckman et al., 2013; Kinsler and Pavan, 2020; Golsteyn et al., 2021; Guo and Qu, 2022), we focus on three potential working channels. First, to measure the classroom environment and teachers' responsiveness, we draw on information from both student and teacher questionnaires to construct three indicators: positive class atmosphere (yes = 1), time spent in lesson preparation (h/week) and total working time (h/week).[9] Parental

[9] Positive class atmosphere (yes = 1) is derived from the student questionnaire, where students are asked to rate to what extent they agree with a positive atmosphere of their classroom on a scale from 1 (strongly disagree) to 4 (strongly agree). If they respond with "somewhat agree" or "strongly agree", assign a value of 1; otherwise, assign a value of 0. Time spent in lesson preparation (h/week) and total working time (h/week) come from self-reported working time per week in the teacher questionnaire.

engagement is measured using three variables: frequent homework guidance (yes = 1), strict discipline (yes = 1), and educational expectations (years).[10] Students' behaviors are measured by learning efforts and non-cognitive abilities. Learning efforts include three variables: often write school homework (yes = 1), often write homework of parents/tutors (yes = 1), and have confidence in the future (yes = 1).[11] Non-cognitive abilities are measured by three variables: social adaptation, externalizing behaviors, and internalizing behaviors.[12]

4.4. Descriptive statistics

It is shown that in the first wave, for an average sample student, 85 % of his/her classmates had ECE experience, and the average ECE duration of these classmates tended to be 2.4 years (Table 1). An average student was around 14 years old in 2013–2014 academic year, with 49 % of them being girls, 10 % being ethnic minorities, 43 % being rural Hukou, 19 % being boarders, and most of them having siblings. 85 % of the sample students had ECE experience themselves. Her/his father and mother had 11.0 and 10.4 years of schooling, respectively. 91 % of their parents were married, and 20 % of students had experienced migration of at least one parent. Moreover, most students (74 %) came from middle-income households. At the classroom level, the average class size was 48, where head teachers were 36 years old on average, had 16.1 years of schooling and 14.8 years of experience on average, with 29 % of them being males.[13]

Table 1
Descriptive statistics.

	Mean (1)	SD (2)	Min (3)	Max (4)	Observations (5)
Panel A: Outcome variables (Grade 8)					
Standardized cognitive score	0.40	0.82	−3.14	2.06	4187
Panel B: Key explanatory variable (Grade 7)					
Classmates' ECE enrolment rate (%)	0.85	0.11	0.37	1.00	4220
Average years of classmates' ECE duration	2.44	0.58	0.63	3.42	4220
0 year	0.16	0.37	0	1	4220
1 year	0.05	0.22	0	1	4220
2 years	0.16	0.37	0	1	4220
3 years	0.36	0.48	0	1	4220
4 years	0.17	0.38	0	1	4220
5 years	0.03	0.18	0	1	4220
Panel C: Covariates (Grade 8)					
Students' characteristics					
Standardized cognitive score *(Grade 7)*	0.15	0.89	−2.03	2.33	4220
Age (months)	167.40	7.73	142	216	4220
Girl (yes = 1)	0.49	0.50	0	1	4187
Ethnic minority (yes = 1)	0.10	0.30	0	1	4220
Number of siblings	0.56	0.73	0	5	4220
Boarding (yes = 1)	0.19	0.39	0	1	4152
ECE experience (yes = 1)	0.85	0.36	0	1	4220
Household characteristics					
Rural Hukou (yes = 1)	0.43	0.50	0	1	4220
Family social economics status (dummy):					
Very poor	0.02	0.15	0	1	4220
Poor	0.08	0.28	0	1	4220
Average	0.74	0.44	0	1	4220
Rich	0.14	0.35	0	1	4220
Very rich	0.01	0.1	0	1	4220
Parental migration (yes = 1)	0.20	0.40	0	1	4220
Years of schooling of fathers	11.04	3.27	0	19	4220
Years of schooling of mothers	10.44	3.50	0	19	4220
Parents married (yes = 1)	0.91	0.28	0	1	4220
Classroom and teacher characteristics					
Class size	48.60	13.05	15	78	4220
Age of Headteacher (yes = 1)	36.21	6.82	22	60	4220
Headteacher is male (yes = 1)	0.29	0.45	0	1	4220
Headteacher's education (years)	16.08	0.70	15	19	4220
Headteacher's teaching experience (years)	14.82	8.93	1	45	4220
Panel D: Mechanism variables (Grade 8)					
Classroom environment and teacher behaviors					
Positive class atmosphere (yes = 1)	0.82	0.39	0	1	4172
Time spent in lesson preparation (h/week)	11.96	6.78	2	35	4187
Total working time (h/week)	49.04	20.05	0	134.8	4187
Parental engagement					
Frequent homework guidance (yes = 1)	0.13	0.33	0	1	4157
Strict discipline (yes = 1)	0.38	0.49	0	1	4126
Educational expectations (years)	16.92	3.21	8	22	4113
Students' behaviors					

(*continued on next page*)

[10] Educational expectations are derived from the parental questionnaire, we draw on the question "What level of education do you hope your child will attain?" and convert expected education levels into years of schoolings, e.g., elementary school = 6 years, academic high school = 12 years, etc. Frequent homework guidance is derived from student questionnaire, "In the last week, did your parents help you with homework every day?". The response of "almost every day" (from the options "never," "1–2 days," "3–4 days," and "almost every day") is coded as 1. Strict discipline is also drawn from the student questionnaire, "How strict are your parents regarding homework and exams?" where "very strict" (from the options "not strict," "strict but not very strict," and "very strict") is coded as 1.

[11] For variables measuring students' learning efforts, often write school homework (yes = 1) and often write homework of parents/tutors (yes = 1) are based on self-reported weekly time allocations in the student questionnaire. If a student reports spending more than 7 h per week on this type of homework, it is assigned a value of 1. The variable "Have confidence in the future (yes = 1)" is also derived from the student questionnaire, where students rate their confidence in the future on a scale from 1 (completely unconfident) to 4 (very confident). If a student responds with "very confident" or "somewhat confident", this variable is coded as 1.

[12] Social adaptation, externalizing behaviors, and internalizing behaviors are derived from the average scores of relevant questions, with details provided in Table A.2.

[13] Our sample is quite representative. Regarding student characteristics, attributes such as the gender and age of the sampled students closely align with national statistics for the same period. According to the Ministry of Education of China (2015), for instance, 47 % of junior high students nationwide were female, 11 % were ethnic minorities, and the average age for Grade 7 students was approximately 13.3 years on average, which is similar to our sample students. Regarding teacher and classroom characteristics, the average class size in junior high schools was 48 students in our sample, consistent with the national average of 48 in junior high schools of China. Additionally, the average years of schooling for junior high school teachers nationwide in 2014 were comparable to those of head teachers in our sample.

Table 1 (*continued*)

	Mean (1)	SD (2)	Min (3)	Max (4)	Observations (5)
Often write school homework (yes = 1)	0.87	0.33	0	1	4187
Often write homework of parents/tutors (yes = 1)	0.24	0.43	0	1	4187
Have confidence in the future (yes = 1)	0.84	0.36	0	1	4132
Students' non-cognitive abilities					
Social adaptation (standardized)	0	1	−3.48	2.09	4220
Externalizing behaviors (standardized)	0	1	−2.89	6.89	4220
Internalizing behaviors (standardized)	0	1	−2.53	2.73	4220
Panel E: Other classmates' characteristics (Grade 7)					
Classmates' proportion of being girls (%)	0.49	0.08	0	0.71	4220
Classmates' proportion of being the only child (%)	0.54	0.26	0	1	4220
Fathers' years of schooling of classmates	11.05	1.93	7.12	15.45	4220
Mothers' years of schooling of classmates	10.44	2.17	4.49	15.19	4220
Classmates' proportion of coming from rich families (%)	0.89	0.15	0.17	1	4220

Notes: The sample involved 52 schools with random class assignments in Grade 7 but did not reassign students in Grade 8.

5. Identification strategy

5.1. Empirical specification

This paper seeks to investigate the spillover effects of classmates' ECE experience on students' cognitive skills.[14] According to the study of Koedel et al. (2015), this study employs a linear value-added model to examine the spillover effects of classmates' ECE experience on students' cognitive skills as follows:

$$Y_{ics}^{G_8} = \beta_0 + \beta_1 \overline{Pre}_{(-i)cs}^{G_7} + Y_{ics}^{G_7} + \gamma Z_{ics} + a_s + \varepsilon_{ics} \quad (2)$$

Where $Y_{ics}^{G_8}$ denotes the cognitive skills of student i in class c, school s (Grade 8). $\overline{Pre}_{(-i)cs}^{G_7}$ denotes classmates' ECE experience of student i (Grade 7, classmates' ECE enrollment rate and classmates' average ECE duration, respectively) excluding student i (indexed by "-i"). $Y_{ics}^{G_7}$ is the baseline cognitive skills of student i (Grade 7). Z_{ics} denotes covariates including three vectors: student characteristics (age, gender, ethnicity, number of siblings, rural Hukou, boarding status and personal ECE experience), household characteristics (years of schooling of both parents, parental marital status, at least one parent migration and household SES), class characteristics (class size, gender, age, education level and experience of head teacher). School fixed effects a_s are included to control for factors at both the school and regional levels that may affect students' cognition. Standard errors are clustered at the school level.

Two potential identification concerns need to be addressed to enable a causal interpretation of the spillover effects of classmates' ECE experience. The first is contextual confounding, including non-random school choice and teacher assignment (Manski, 1993). The former implies that parents sending their children to preschool might be more likely to select junior high school for them. The latter means principals have the incentive to assign quality teachers to classes with higher ECE enrollment rates to improve school performance in exams. To address the concern, we control the school fixed effects to exploit the random within-school variation of classmates' ECE experience, together with a series of teacher characteristics in Eq. (1). The second is endogenous sorting (Manski, 1993), which might pose a threat to the randomness of class assignments. For example, if the class assignments are based on some unobserved factors affecting both the classmates' ECE experience and students' cognition, the observed correlation does not imply the causal relationship. Thus, we test for the validity of random class assignment in the following section.

5.2. Evidence of random class assignment

Three potential identification concerns need to be addressed to enable a causal interpretation of the spillover effects of classmates' ECE experience: the effectiveness of random class assignment, the randomness of class resource allocation, and variation in educational resources. The first concern is the validity of random class assignment. For instance, if two homeroom teachers, perhaps under pressure from the school, assigned students based on academic performance but reported otherwise, then the assignment cannot truly be considered random. To address this, we follow Gong et al. (2021) and Guo et al. (2022) by conducting a series of falsification tests based on a counterfactual

Table 2
Random class assignment test.

	Cognitive score (Grade 7)			
	(1)	(2)	(3)	(4)
Panel A: Schools randomly assigned classes in Grade 7 but did not reassign students in Grade 8				
Classmates' ECE enrolment rate (7th)	2.434***	0.838		
	(0.114)	(0.602)		
Classmates' average ECE duration (7th)			0.564***	−0.022
			(0.022)	(0.027)
Student characteristics (CHs)	No	Yes	No	Yes
Household CHs	No	Yes	No	Yes
Class CHs	No	Yes	No	Yes
School FE	No	Yes	No	Yes
N	4220	4152	4220	4152
R^2	0.098	0.280	0.135	0.278
Panel B : Schools with two Grade 7 classes but have been excluded from our sample				
Classmates' ECE enrolment rate (7th)	1.864***	0.577***		
	(0.044)	(0.112)		
Classmates' average ECE duration (7th)			0.533***	0.161***
			(0.013)	(0.035)
Student CHs	No	Yes	No	Yes
Household CHs	No	Yes	No	Yes
Class CHs	No	Yes	No	Yes
School FE	No	Yes	No	Yes
N	5527	4826	5527	4826
R^2	0.242	0.686	0.225	0.685

Notes: (1) CHs stands for characteristics, FEs stands for fixed effects. (2) The sample students in Panel A come from 52 schools randomly assigned classes in Grade 7 but did not reassign their students in Grade 8. Sample students in Panel B come from 57 schools with two Grade 7 classes but were excluded later from our study sample. (3) Student characteristics include cognitive score (Grade 7), age, gender, ethnicity, number of siblings, boarding status, and ECE experience of themselves. Household characteristics include hukou, years of schooling of both parents, parental marital status and at least one parent migration, family social economics status. Class characteristics include class size, head teacher' s age, gender, years of schooling, and teaching experience. (4) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

[14] Following Clark and Loheac (2007), we assume it takes about one year for classmates' ECE experience to manifest its impact on students' cognitive outcomes.

Table 3
Effects of classmates' ECE experience in Grade 7 on adolescents' cognitive abilities in Grade 8.

	Cognitive score (Grade 8)					
	(1)	(2)	(3)	(4)	(5)	(6)
Classmates' ECE enrolment rate (7th)	0.859***	0.855***	0.657**			
	(0.287)	(0.279)	(0.317)			
Classmates' average ECE duration (7th)				0.155*	0.154*	0.091
				(0.087)	(0.085)	(0.080)
Cognitive score (7th)	0.363***	0.359***	0.358***	0.363***	0.359***	0.358***
	(0.026)	(0.025)	(0.025)	(0.026)	(0.025)	(0.025)
Age (months)	−0.011***	−0.010***	−0.010***	−0.011***	−0.011***	−0.011***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Girl (yes = 1)	0.042*	0.039*	0.039*	0.043*	0.040*	0.040*
	(0.022)	(0.022)	(0.022)	(0.022)	(0.022)	(0.022)
Ethnic minority (yes = 1)	−0.004	−0.011	−0.017	0.002	−0.006	−0.014
	(0.048)	(0.048)	(0.048)	(0.049)	(0.049)	(0.049)
Number of siblings	−0.016	−0.004	−0.003	−0.019	−0.007	−0.005
	(0.018)	(0.019)	(0.019)	(0.018)	(0.020)	(0.019)
Boarding (yes = 1)	0.010	0.020	0.023	0.000	0.011	0.017
	(0.051)	(0.053)	(0.053)	(0.049)	(0.051)	(0.051)
ECE experience (yes = 1)	0.123***	0.119***	0.116***	0.124***	0.121***	0.115***
	(0.032)	(0.032)	(0.032)	(0.032)	(0.033)	(0.032)
Rural Hukou (yes = 1)		0.027	0.027		0.026	0.027
		(0.025)	(0.025)		(0.025)	(0.025)
Parental migration (yes = 1)		−0.047	−0.044		−0.048*	−0.044
		(0.029)	(0.029)		(0.028)	(0.029)
Years of schooling of fathers		0.004	0.003		0.003	0.003
		(0.005)	(0.005)		(0.005)	(0.005)
Years of schooling of mothers		0.012**	0.012**		0.012**	0.012**
		(0.005)	(0.005)		(0.005)	(0.005)
Parents married (yes = 1)		−0.019	−0.020		−0.023	−0.023
		(0.042)	(0.042)		(0.043)	(0.043)
Class size			0.004			0.006
			(0.006)			(0.006)
Age of head teacher			0.005			0.007
			(0.005)			(0.006)
Headteacher is male (yes = 1)			−0.043			−0.047
			(0.059)			(0.063)
Headteacher's education (years)			−0.003			−0.013
			(0.021)			(0.019)
Headteacher's teaching experience (years)			0.001			0.001
			(0.003)			(0.003)
Household SES	Yes	Yes	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes	Yes	Yes
Constant	1.244***	1.021***	0.850*	1.606***	1.385***	1.211**
	(0.360)	(0.351)	(0.488)	(0.379)	(0.369)	(0.515)
N	4120	4120	4120	4120	4120	4120
R^2	0.447	0.450	0.451	0.445	0.448	0.450

Notes: (1) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

framework. The first counterfactual test examines whether random class assignment affects baseline cognitive ability by analyzing classes that were randomly assigned and were not undergoing random assignment, respectively. Since peer effects require time to develop (Gong et al., 2021; Guo et al., 2022), we do not expect to observe any spillover effects immediately in Grade 7 for the randomly assigned classes.

As shown in Table 2A, classmates' ECE experience does not predict baseline cognitive scores after controlling for student, household, and class characteristics and including school fixed effects. Moreover, falsification test in schools excluded from our sample due to non-random assignment shows that classmates' ECE experience significantly predicts Grade 7 students' cognitive outcomes (Table 2B). This is due to students in these classes may have been grouped based on prior achievement or other observable characteristics, which are highly correlated with cognitive ability. This counterfactual test supports evidence of random class assignment.

The second test is randomly re-assigning students in the 52 sample schools to two classes 1000 times as a placebo test. As can be seen in Fig. A.1, the standard deviation fraction of ECE experience basically follows a normal distribution with a mean of 0.109, which is close to the actual standard deviation in our study sample (0.110), further validating the random class assignment.

Additionally, it was essential to check whether educational resources were evenly distributed across classes in each school to avoid potential biases in estimating the effects of classmates' ECE experience. For this, we analyzed the correlation between household and student-level characteristics and five class-level attributes: class size, age, gender, educational background and experience of the homeroom teachers (following Wang et al., 2018; Wang and Zhu, 2021). Results in Table A.1 show that, only three coefficients were statistically significant, suggesting that resources were generally balanced across classes in our sample schools.

Finally, as our empirical design compares students' cognitive outcomes between classes within the same schools, there is also a concern that one sample class might have a higher proportion of classmates attending ECE than the other class by chance. To address this, we evaluated the adequacy of within-school variation in classmates' ECE composition by regressing their ECE composition on school fixed effects and examining the residuals. As shown in Fig. A.2, which plots the residual distributions of classmates' ECE enrollment rates and average ECE duration, respectively, there is a sufficient variation within schools, confirming the robustness of our approach.

Overall, these validation tests confirm that both students and educational resources were randomly assigned across Grade 7 classes in

Table 4
Underlying mechanisms: classroom dynamics and parental engagement.

Panel A: Class level (8th)	Positive class atmosphere (yes = 1)		Time spent in lesson preparation of headmaster (h/week)		Total working time of headmaster (h/week)	
	(1)	(2)	(3)	(4)	(5)	(6)
Classmates' ECE enrolment rate (7th)	0.326** (0.164)		1.588 (12.19)		35.721 (23.202)	
Classmates' average ECE duration (7th)		0.061 (0.049)		3.883 (3.377)		8.290 (7.002)
Student CHs	Yes	Yes	Yes	Yes	Yes	Yes
Household CHs	Yes	Yes	Yes	Yes	Yes	Yes
Class CHs	Yes	Yes	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes	Yes	Yes
N	4077	4077	4120	4120	4120	4120
R^2 / R^2 pseudo	0.106	0.105	0.475	0.488	0.619	0.618
Panel B: parental level (8th)	Educational expectations (years)		Frequent homework guidance (yes = 1)		Strict discipline (yes = 1)	
	(7)	(8)	(9)	(10)	(11)	(12)
Classmates' ECE enrolment rate (7th)	1.132 (1.103)		0.207* (0.123)		−0.011 (0.109)	
Classmates' average ECE duration (7th)		0.078 (0.258)		0.025 (0.031)		−0.017 (0.032)
Student CHs	Yes	Yes	Yes	Yes	Yes	Yes
Household CHs	Yes	Yes	Yes	Yes	Yes	Yes
Class CHs	Yes	Yes	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes	Yes	Yes
N	4049	4049	3955	3955	4062	4062
R^2 / R^2 pseudo	0.185	0.185	0.153	0.153	0.043	0.043

Notes: (1) CHs stands for characteristics, FEs stands for fixed effects. (2) Student characteristics include cognitive score (Grade 7), age, gender, ethnicity, number of siblings, boarding status, and ECE experience of themselves. Household characteristics include hukou, years of schooling of both parents, parental marital status and at least one parent migration, family social economics status. Class characteristics include class size, head teacher' s age, gender, years of schooling, and teaching experience. (3) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

the sample schools. Additionally, there is considerable variation in classmates' ECE experience, which supports our identification strategy, providing us with a unique opportunity to estimate the impact of classmates' ECE experience on students' cognitive outcomes in junior high school.

6. Results and discussion

6.1. Main results

We find that classmates' ECE experiences have a significant and positive impact on adolescents' cognitive ability (Table 3). To be specific, a ten-percentage-point (pp) increase in classmates' ECE enrollment rate is associated with the increase in one's cognitive scores by 0.080 SD,[15] indicating that classmates' ECE experience positively affect students' cognitive abilities. Notably, personal ECE experience is also significantly associated with cognitive abilities, consistent with previous studies (Deming, 2009; Blanden et al., 2016; Drange and Havnes, 2019; Barnett and Jung, 2021). Moreover, girls with younger, more educated mothers tend to achieve higher cognitive scores. Their cognitive abilities are not influenced by the characteristics of their homeroom teachers.

Given the spillover effects of classmates' ECE experience, to what extent do these effects lead to an underestimation of the cognitive benefits of ECE attendance? Following Neidell and Waldfogel (2010), it is estimated that when classmates' ECE enrolment rate increases from the current proportion (85 %) to 100 %, the resulting cognitive benefits account for 80–85 % of the private benefits of personal ECE experience.2 Therefore, this kind of spillover effects is statistically significant and cannot be overlooked. Compared with previous studies, this proportion is slightly lower than the findings of 70–80 % of Williams (2019) but higher than that of 18–30 % of Neidell and Waldfogel (2010). The discrepancy might be because Neidell and Waldfogel (2010) focused on children aged six years old, while the private cognitive benefits of ECE decline significantly with age (Barnett and Jung, 2021).

Moreover, adolescents' cognitive abilities do not significantly improve with the increase of their classmates' ECE duration (Table 3). To explore this further, we examined the non-linear effects of classmates' average ECE duration on cognitive abilities. As shown in Fig. A.3, the benefits are mainly driven by classmates with at least three years of ECE experience, which highlights the importance of completing a full three years of ECE.[16] However, as shown in Table 1, only 36 % of students attended three years of ECE, which may explain the overall insignificant spillover effect of classmates' ECE duration to some extent.

6.2. Potential mechanisms

Our findings suggest that classmates' ECE experience generates beneficial spillover effects on individual cognitive ability. What are the underlying mechanisms driving these effects? To what extent does each mechanism contribute to the total effect? In this section, we first examine the following underlying channels: (a) classroom environment dynamics, (b) parental investment responses, and (c) individual behavioral adjustments. Drawing on the method proposed by Heckman et al. (2013), we then estimate each channel's marginal contribution to the total effect. Finally, we examine the role of peer interactions within social networks in shaping the spillovers.

6.2.1. Classroom dynamics

To test the above potential working channels, we first seek to examine whether classmates' ECE experience drives the classroom environment and leads to teachers' responsiveness to these classes (Table 4). As shown in Panel A, with higher proportion of classmates with ECE experience, adolescents are more likely to think their classrooms have a positive atmosphere. These findings align with those of Gong et al. (2021) and Opper (2019), supporting the channel of changes in the classroom dynamics.

6.2.2. Parental engagement: education involvement and expectations

Given the positive response of classroom environment and teacher

[15] This coefficient is lower than the estimates of Wang (2021) (0.101) and Zhang et al. (2023) (0.083). Due to their studies did not draw on the random class assignment within the same school to conduct a careful selection of the analytical sample or not rely on value-added models to control for students' baseline performance, our results are relatively more reliable.

[16] To further distinguish the heterogenous effects of different ECE dosage of classmates, we categorized classmates' ECE duration into five groups (1, 2, 3, 4, and 5 years), drawing on those with zero years of ECE experience as the reference group. The results are presented in Fig. A.3.

Table 5
Underlying mechanisms: students' learning efforts and non-cognitive skills.

Panel A: Learning efforts (8th)	Often write school homework (yes = 1)		Often write homework of parents/tutors (yes = 1)		Have confidence in the future (yes = 1)	
	(1)	(2)	(3)	(4)	(5)	(6)
Classmates' ECE enrolment rate (7th)	0.251**		0.158		−0.055	
	(0.119)		(0.135)		(0.104)	
Classmates' average ECE duration (7th)		0.094***		−0.024		−0.006
		(0.026)		(0.030)		(0.029)
Student CHs	Yes	Yes	Yes	Yes	Yes	Yes
Household CHs	Yes	Yes	Yes	Yes	Yes	Yes
Class CHs	Yes	Yes	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes	Yes	Yes
N	4086	4086	4120	4120	4068	4068
R^2 / R^2 pseudo	0.167	0.169	0.058	0.058	0.078	0.078

Panel B: non-cognitive skills (8th)	Social adaptation		Externalizing behaviors		Internalizing behaviors	
	(7)	(8)	(9)	(10)	(11)	(12)
Classmates' ECE enrolment rate (7th)	0.839***		−0.503*		−0.169	
	(0.246)		(0.262)		(0.344)	
Classmates' average ECE duration (7th)		0.135*		−0.117		−0.015
		(0.073)		(0.078)		(0.089)
Student CHs	Yes	Yes	Yes	Yes	Yes	Yes
Household CHs	Yes	Yes	Yes	Yes	Yes	Yes
Class CHs	No	Yes	No	Yes	No	Yes
School FE	Yes	Yes	Yes	Yes	Yes	Yes
N	4120	4120	4120	4120	4120	4120
R^2 / R^2 pseudo	0.255	0.253	0.103	0.103	0.054	0.054

Notes: (1) CHs stands for characteristics, FEs stands for fixed effects. (2) Student characteristics include cognitive score (Grade 7), age, gender, ethnicity, number of siblings, boarding status, and ECE experience of themselves. Household characteristics include hukou, years of schooling of both parents, parental marital status and at least one parent migration, family social economics status. Class characteristics include class size, head teacher' s age, gender, years of schooling, and teaching experience. (3) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

behavior to classmates' ECE experiences, an interesting question arises: Do parents adjust their behaviors in response to changes in the composition of their children's classmates? In Panel B of Table 4, we find that a higher proportion of classmates with ECE experience in Grade 7 significantly increases the likelihood of parental engagement in more frequent homework guidance. Meanwhile, the effect on educational expectations is insignificantly positive, and that on strict discipline is marginally negative but insignificant. Although these results remain speculative, they are consistent with those of Guo and Qu (2022), which suggest that increased educational investment of peers will encourage parents to become more engaged in educational competition, thus encourage them to engage more actively in supporting children's academic performance.

6.2.3. *Students' behaviors: learning efforts and non-cognitive abilities*

Whether changes in classroom environment, teacher behavior, and parental involvement, which are driven by the spillover effects of ECE, would further lead to changes in students' behaviors? In Table 5, we replace the dependent variables with learning effort, having confidence in the future and non-cognitive ability (including social adaptation, externalizing behaviors, and internalizing behaviors) to test the possibility. Results in Panel A show that both an increase in the proportion of classmates' ECE enrolment rate and a longer average ECE duration of classmates lead adolescents to allocate more time into school homework, consistent with the findings of Zhang et al. (2023). However, this spillover effect is not observed in the time allocated to other types of homework or in students' confidence in the future.

Moreover, in Panel B, we observe significant spillover effects of classmates' ECE experience on adolescents' non-cognitive skills. Specifically, after controlling for school fixed effects and a set of covariates, a 10-percentage-point increase in the proportion of classmates with ECE experience is associated with a 0.08 SD increase in adolescents' social adaptation scores and a 0.05 SD decrease in their externalizing behavior scores. These findings provide a plausible explanation for the cognitive spillover effects of ECE: having more classmates with ECE experience can enhance students' skills in social adaptation, socialization and encourage them to interact with others. Many previous studies have shown that such improvements in non-cognitive skills form an essential foundation for the development of cognitive abilities (Cunha et al., 2010; Golsteyn et al., 2021; Kautz et al., 2014).

6.2.4. *Interactions in social networks*

Social network interactions are a significant determinant of peer effects (Opper, 2019). We suppose that, if the spillovers predominately occur within groups of friends, peer-to-peer interactions could be an important channel for the spillover effects of ECE. Since the CEPS does not contain public available information on students' friendship, we draw on the fact that students are more likely to be friends with peers who share similar traits. Therefore, we subdivide each cohort by gender and parental education, construct four mutually exclusive sub-groups of classmates and then construct four different measures of classmates' ECE experience within each sub-group.[17] In this case, we replace the original independent variable with the four variables outlined above and re-run the regression, following the specification in Eq. (2).

We find that the abovementioned spillover effects of ECE are indeed driven by classmates with ECE experience within homogeneous subgroups (Table 6). Panel A shows that in terms of the effects of classmates' ECE enrolment rate, only in the subgroup where classmates have the same gender and same family SES as the student under discussion

[17] To be specific, we first divide the sample students into "high parental education" and "low parental education" groups based on the median of their parents' average years of schooling. Then, we construct the following four measures: one is for students who are their same gender and parental education groups, one is for those of the same parental education groups but different gender, one for those students of the same gender but different level of parental education, and one for those who are both a different level of parental education and different gender. These measures are constructed in the same way as the main independent measure was constructed. In subsequent robustness checks, we also divide the sample adolescents into two groups based on gender (or parental education) and construct measures of classmates' ECE experience within each group as described previously.

Table 6
Spillover effects of classmates' ECE experience within homogeneous sub-groups.

Outcome:	Cognitive score (8th)	
Dependent variable:	Classmates' ECE enrolment rate (7th) (1)	Classmates' average ECE duration (7th) (2)
Panel A: Classmates' ECE experience in the following four sub-groups (7^{th}):		
Different gender and different family SES	0.050	0.023
	(0.070)	(0.018)
Different gender and same family SES	−0.068	0.012
	(0.114)	(0.030)
Same gender and different family SES	0.098	0.010
	(0.077)	(0.023)
Same gender and same family SES	0.189*	0.013
	(0.109)	(0.025)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	3623	3380
R^2	0.436	0.425
Panel B: Classmates' ECE experience in the following sub-groups by gender (7^{th}):		
Different gender	0.192	0.051
	(0.158)	(0.045)
Same gender	0.338**	0.017
	(0.162)	(0.053)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	4119	3842
R^2	0.451	0.440
Panel C: Classmates' ECE experience in the following sub-groups by family SES (7^{th}):		
Different family SES	0.104	0.036
	(0.109)	(0.031)
Same family SES	0.174	0.034
	(0.159)	(0.044)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	3944	3677
R^2	0.447	0.436

Notes: (1) CHs stands for characteristics, FEs stands for fixed effects. (2) Student characteristics include cognitive score (Grade 7), age, gender, ethnicity, number of siblings, boarding status, and ECE experience of themselves. Household characteristics include hukou, years of schooling of both parents, parental marital status and at least one parent migration, family social economics status. Class characteristics include class size, head teacher' s age, gender, years of schooling, and teaching experience. (3) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

where the estimates come out statistically significant. ECE experience of classmates most similar to the students, e.g., the group of "same gender and same education of both parents", has the largest positive impact on students' cognitive abilities. Also, the effects of classmates' ECE duration come out insignificant. Panel B and C further support that the cognitive spillover effect is greater when peers in the same group as students. Nevertheless, it should be kept in mind that these results are just preliminary, and further studies are needed to explore the detailed processes of peer interactions within the classroom.

Taken together, our findings provide evidence that classmates' ECE experience helps improve the class environment, encourage parents to invest more effort in students' academic success, and then promote students' learning efforts and non-cognitive skills. These results help us enhance the understanding of the potential mechanisms by which classmates' ECE experience promotes students' cognitive abilities.

6.2.5. Relative explanatory power of mechanisms

Our results have shown that exposure to classmates with ECE experience or a longer ECE duration works through the following possible channels, classroom dynamics, parental engagement, students' learning efforts and non-cognitive skills, which in turn influence students' cognitive ability. To further calculate the ratio of different mechanisms' explanatory power, we employ a decomposition method proposed by Heckman et al. (2013) and Gong et al. (2021) as follows. First, we denote m^j_{ics} as the mechanism variable j and use the following estimation specification to estimate the coefficients of θ^j_1 :

$$m^j_{ics} = \theta_0 + \theta^j_1 \overline{Pre^{G_7}_{(-i)cs}} + \theta^j_2 Y^{G_7}_{ics} + \gamma Z_{ics} + a_s + \varepsilon_{ics} \quad (3)$$

Next, we incorporate all relevant mechanism variables into Eq. (2) and consider the following specification to estimate coefficients of ζ^j:

$$Y^{G_8}_{ics} = \alpha_0 + \alpha_1 \overline{Pre^{G_7}_{(-i)CS}} + \alpha_2 Y^{G_7}_{ics} + \gamma Z_{ics} + \sum_j \zeta^j m^j_{ics} + a_s + \varepsilon_{ics} \quad (4)$$

Using the estimated coefficients of $\widehat{\theta^j_1}$ and $\widehat{\zeta^j}$, we can calculate the explanatory power of mechanism j for peer effect as $\frac{\widehat{\theta^j_1}\widehat{\zeta^j}}{\widehat{\beta_1}}$,where $\widehat{\beta_1}$ denotes the estimated coefficient from the estimation of Eq. (2).

Fig. 6 presents a decomposition of the cognitive spillover effects into potential mechanisms and other factors. As shown in Panel A, students' behaviors account for the largest share (13 %), with learning efforts and non-cognitive abilities contributing 7 % and 6 %, respectively. Classroom dynamics explain approximately 10 %, while parental engagement accounts for 6 %. Taken together, these mechanisms explain 30 % of total spillover effects, with the remainder unexplained. As a robustness check, Panel B provides a similar decomposition for the spillover effects of classmates' average ECE duration, and the results are consistent with those in Panel A.

6.3. Heterogeneity in spillover effects of classmates' ECE experience

Increasing evidence has shown that peer effects differ a lot by individual and household characteristics (Black et al., 2013; Ding and Lehrer, 2007; Carman and Zhang, 2012; Gong et al., 2021; Wang and Zhu, 2021). Here we explore the potential heterogeneous impacts of classmates' ECE experience on students' cognitive skills by adding interaction terms on our analyses in Table 3. To be specific, we focus on four indicators, including gender, ECE experience, hukou status and education years of both parents, respectively.

6.3.1. By personal characteristics

Results from heterogeneous impacts by personal characteristics show some informative patterns (Table 7). First the effects don't vary by gender (Panel A). In the meantime, those with ECE experience themselves benefit more from classmates' ECE experience, whether considering the effects of enrolment rate and duration (Panel B). One possible explanation might be that those with ECE experience are more likely to adapt to the interactions with their peers with similar ECE experiences, thereby deriving greater positive cognitive spillover effects from these interactions.

6.3.2. By household characteristics

Heterogeneous effects by household characteristics are presented in Table 8, where some different findings emerge. For instance, both rural and urban hukou students benefit similarly from classmates' ECE experience, in terms of both the enrolment rate and duration (Panel A) Additionally, we find that students with higher levels of education of both parents benefit more from increases in classmates' ECE enrollment rate and duration (Panel B), which appears inconsistent with Hypothesis 2. This may be because that more educated parents are more likely to prioritize early childhood development and choose higher-quality ECE programs.

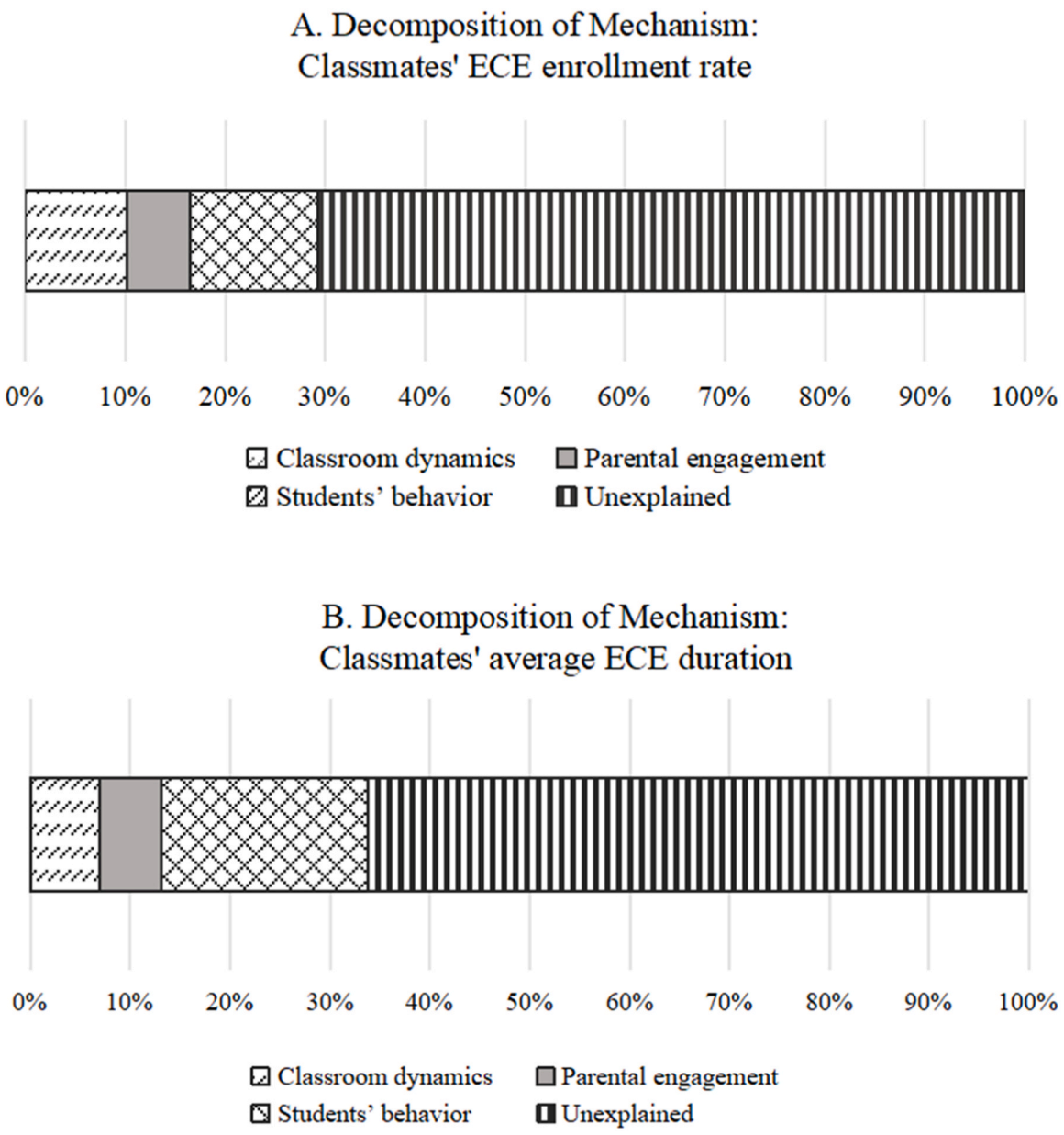

Fig. 6. Decomposition of underlying mechanism.

6.3.3. By school characteristics

Moreover, heterogeneity analyses by school-level characteristics are reported in Table A.3. We find that classmates' ECE experience has a significant positive spillover effect in urban schools, but not in rural schools. In contrast, no significant differences are observed across schools with different levels of per-student public funding or student-teacher ratio, both of which are commonly indicators of school quality. These findings might be more likely driven by differences in pre-school education quality (Wong et al., 2013; Hu et al., 2014; Li et al., 2016; Rao et al., 2017), rather than in junior high school resources.

6.4. Robustness Checks

Whether the observed spillover effects of ECE can be driven by other peer characteristics? There has been some evidence that individual personalities and other household characteristics (Golsteyn et al., 2021; Gong et al., 2021; Wang and Zhu, 2019) might affect adolescents' cognitive or non-cognitive performance. If these kinds of characteristics correlate with classmates' ECE composition, the observed cognitive spillover effects might be biased. To deal with the concern, we reran the Eq. (2) by including array of pre-determined peer characteristics as a robustness check, including classmates' proportion of being girls (%), classmates' proportion of being the only child (%), fathers' years of schooling of classmates, mothers' years of schooling of classmates and proportion of classmates coming from rich families. As shown in Table A.4, we find from the robustness check that the estimates of effects of classmates ECE experience remained the same with those added peer characteristics, indicating that the observed cognitive spillover effects of ECE cannot be driven by other peer characteristics.

We also conducted a robustness check by replacing OLS regression with quantile regression. It has been shown that peer effects vary across the distribution of individual ability (Ding and Lehrer, 2007). To examine whether this could introduce bias in our OLS estimates, we re-estimated Eq. (2) using quantile regression at intervals of 0.05, from the 0.05–0.95 quantile. Results in Table A.5 indicate that positive cognitive spillover effects from classmates' ECE experience exist across different levels of cognitive ability, and those in higher quantiles experience smaller gains than those in lower quantiles of cognitive abilities

Table 7
Heterogenous analyses by personal characteristics.

	Cognitive score (8th)	
	(1)	(2)
Panel A: by gender		
Classmates' ECE enrolment rate (7th)	0.597*	
	(0.326)	
Classmates' ECE enrolment rate (7th)×gender	0.112	
	(0.189)	
Classmates' average ECE duration (7th)		0.101
		(0.078)
Classmates' average ECE duration (7th)×gender		0.001
		(0.042)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	4087	3814
R^2	0.451	0.440
Panel B: by personal ECE experience		
Classmates' ECE enrolment rate (7th)	−0.187**	
	(0.092)	
Classmates' ECE enrolment rate (7th)×personal ECE experience	0.074**	
	(0.036)	
Classmates' average ECE duration (7th)		−0.246***
		(0.091)
Classmates' average ECE duration (7th)×personal ECE experience		0.099***
		(0.034)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	4120	4120
R^2	0.452	0.451

Notes: (1) The personal ECE experience is categorized based on the years attended, where students with 1–2 years are classified as the shorter preschool group, and those with 3–5 years as the longer preschool group. (2) CHs stands for characteristics, FEs stands for fixed effects. (3) Student characteristics include cognitive score (Grade 7), age, gender, ethnicity, number of siblings, boarding status, and ECE experience of themselves. Household characteristics include hukou, years of schooling of both parents, parental marital status and at least one parent migration, family social economics status. Class characteristics include class size, head teacher' s age, gender, years of schooling, and teaching experience. (4) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8
Heterogenous analyses by household characteristics.

	Cognitive score (8th)	
	(1)	(2)
Panel A: by hukou status		
Classmates' ECE enrolment rate (7th)	0.553	
	(0.374)	
Classmates' ECE enrolment rate (7th) ×hukou status	0.189	
	(0.254)	
Classmates' average ECE duration (7th)		0.090
		(0.085)
Classmates' average ECE duration (7th)×hukou status		0.002
		(0.046)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	4120	4120
R^2	0.451	0.450
Panel B: by education years of both parents		
Classmates' ECE enrolment rate (7th)	0.445	
	(0.311)	
Classmates' ECE enrolment rate (7th) ×education years of both parents	0.602***	
	(0.206)	
Classmates' average ECE duration (7th)		0.050
		(0.082)
Classmates' average ECE duration (7th)×education years of both parents		0.105**
		(0.045)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	4120	4120
R^2	0.449	0.448

Notes:
The hukou status is divided by students' hukou (urban/rural). The education years of both parents is based on the median of their parents' average years of schooling, where those above the median are classified as the high parental education group, and those below the median as the low parental education group. (2) CHs stands for characteristics, FEs stands for fixed effects. (3) Student characteristics include cognitive score (Grade 7), age, gender, ethnicity, number of siblings, boarding status, and ECE experience of themselves. Household characteristics include years of schooling of both parents, parental marital status and at least one parent migration, family social economics status. Class characteristics include class size, head teacher' s age, gender, years of schooling, and teaching experience. (4) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

(Fig. A.4). Notably, the strongest gains appear at the 0.50 quantile, showing that students with moderately below-average cognitive abilities benefit the most, consistent with findings of Ding and Lehrer (2007) and Carman and Zhang (2012). Overall, our results are robust to various model specifications.

6.5. Cost-benefit analysis

We now employ our estimates to calculate the cost and return of ECE provision, considering both direct (personal) and indirect (spillover) benefits (Table 9). We measure the per-child cost of ECE provision through two approaches: national average cost and the cost of implementing rural ECE programs.[18] Under different approaches, the per-child costs (2010 values) are $1037 and $905, respectively.

To evaluate the benefits, we derive the private benefit (2010 value) of $1758 by combining: (1) lifetime income of an average Chinese people from the China Family Panel Studies (CFPS), (2) the cognitive returns to ECE calculated in Tables 3, and (3) the labor market returns to cognitive skills reported by Kline and Walters (2016). When considering only private returns, the cost-benefit ratio ranges from 1.8:1–2.0:1. After incorporating cognitive spillover effects, this ratio increases substantially to 3.2:1–3.7:1 (Table 9). These results suggest that ECE in China generates significant net gains relative to its costs even when accounting solely for cognitive benefits. Moreover, omitting spillover effects would lead to significant underestimation of ECE investment returns.

We acknowledge that these back-of-the-envelope calculations likely underestimate the true benefits. First, while our analysis focuses on cognitive skills, ECE may yield additional human capital benefits (e.g., health) and social benefits (e.g., reduced crime rates). Second, we only examine classroom-level spillovers, whereas such effects may also operate in other contexts like households (Garces et al., 2002). These considerations further reinforce the conclusion that ECE programs in China are highly cost-beneficial.

7. Conclusion and implications

In this paper, we investigated the cognitive spillover effects of classmates' ECE experience on junior high school adolescents in China. Using data from CEPS, we drew on the value-added framework and a

[18] Given that rural areas remain the most disadvantaged in terms of ECE provision, cost estimates based on rural programs provide a more realistic assessment of future investment needs. In the absence of official statistics on the costs of rural ECE programs, we follow Chen et al. (2019, 2022) and use cost estimates from the One Village One Preschool (OVOP) pilot program, one of the few large-scale ECE interventions implemented in rural China.

Table 9
The cost and return of ECE.

Item		Method 1 (National average cost)	Method 2 (OVOP pilot cost)	Data Sources
Cost				
(1)	Cost (CNY per child per year)	¥2880 (2011)	¥2500 (2009)	National avg. cost: Ministry of Education (per-student expenditure) OVOP pilot cost: China Development Research Foundation
(2)	USD Equivalent	$446	$366	(1)/Exchange rate (2011: 6.46 CNY/USD; 2009: 6.83 CNY/USD)
(3)	Discounted to 2010	$432	$377	
(4)	Cost per child in 2010	$1037	$905	(3) × 2.4 years (Avg. duration in Table 1)
Benefits				
(5)	Lifetime Income PV in 2010	$124,675	$124,675	Lifetime income 2 million CNY (CFPS 2020) 40 working years discounted
(6)	Cognitive Gain of ECE	0.141 SD	0.141 SD	Calculated in Table 3
(7)	Private Benefit in 2010	$1758	$1758	Cognitive skills: + 1 SD = Income + 10 % (Kline and Walters, 2016) (5) × (6) × 0.1
Benefit-Cost Ratio				
(8)	Private Return Only	1.8:1	2.0:1	(7) / (3)
(9)	Including Spillovers	3.2:1–3.3:1	3.6:1–3.7:1	(8) × 1.80 - (8) × 1.85

quasi-experimental approach of random class assignments to address potential endogeneity issues. Our findings show that classmates' ECE experience significantly enhances adolescents' cognitive performance, as measured by ECE enrollment rate and average duration, respectively. Neglecting cognitive spillovers from ECE leads to underestimating the broader benefits of ECE attendance. That said, the spillover effects of increasing classmates' ECE enrollment from 85 % to full participation (100 %) account for 80–85 % of the ECE's private cognitive benefits. Moreover, cognitive spillovers of ECE are facilitated by various mechanisms, including improved classroom environment, enhanced involvement from parents, increased learning efforts and non-cognitive skills of students and social interactions within peer networks. Additionally, students with ECE experience, those from better educated families and urban schools with below-average cognitive abilities in Grade 7 benefited more from their peers' ECE experience.

We acknowledge three limitations of this study. The first is that data constraints have limited us to investigate the longer-term spillover effects of classmates' ECE experience in Grade 7 on adolescents' cognitive skills and other performance in the labor market. Future studies are needed to explore whether classmates' ECE experience has varying impacts across developmental stages as adolescents progress through higher grades or transition to the workforce. The second limitation is that, as our results indicate, the spillover effects might be driven by classmates with ECE experience within more homogeneous sub-groups. Further exploration of peer interactions within friendship networks would provide a deeper understanding of underlying mechanisms of the spillovers. Finally, given the considerable variation in ECE quality that Chinese students experience (Rao et al., 2017), it is essential to integrate information on the quality of ECE attended by students and further examine the heterogeneous spillover effects of peers attending ECE by different qualities.

Despite its limitations, our study provides actionable insights for both the policymakers and schools to take into account classmates' ECE experience when determining or adjusting peer composition in classrooms, in order to enhance adolescents' cognitive development. As for policymakers, given the non-negligible cognitive spillover effects of ECE, fiscal resource allocations for education must explicitly incorporate these spillovers to avoid underestimating the benefits of ECE investments. That said, the "pie" of ECE needs to be expanded and improved to ensure universal access and sufficient duration, thereby maximizing its benefits. Moreover, as disadvantaged students (e.g., left-behind children) tend to benefit more from cognitive spillovers, ensuring equitable access to ECE for these populations should be a policy priority. Notably, children in rural schools appear to benefit less from spillover effects, likely due to persistent disparities in ECE quality between urban and rural areas. This highlights the need for specific efforts to address the quality gap. As for schools, our findings on cognitive spillovers suggest that strategically grouping students with peers who have ECE experience could serve as a low-cost intervention to mitigate cognitive deficits. Finally, since positive classroom environments and supportive peer interactions amplify the ECE spillover effects, schools should adopt practices that actively cultivate such peer interactions to maximize benefits.

CRediT authorship contribution statement

Chengfang Liu: Supervision, Methodology, Formal analysis, Conceptualization. **Yuhe Guo:** Software, Data curation, Conceptualization. **Xinmeng Hao:** Data curation, Writing – review & editing, Formal analysis. **Yalin Tang:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT 4o in order to polish the manuscript slightly. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Authors statement

We, the authors of this manuscript, confirm that all authors contributed equally to all stages of the research and preparation of this article, including conceptualization, data collection, analysis, and writing. We affirm that this work is original, has not been published previously, and is not under consideration for publication elsewhere. There are no conflicts of interest, financial or otherwise, that could have influenced the research or interpretation of results. All ethical standards applicable to this study have been strictly adhered to, ensuring compliance with institutional and international guidelines.

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Appendices

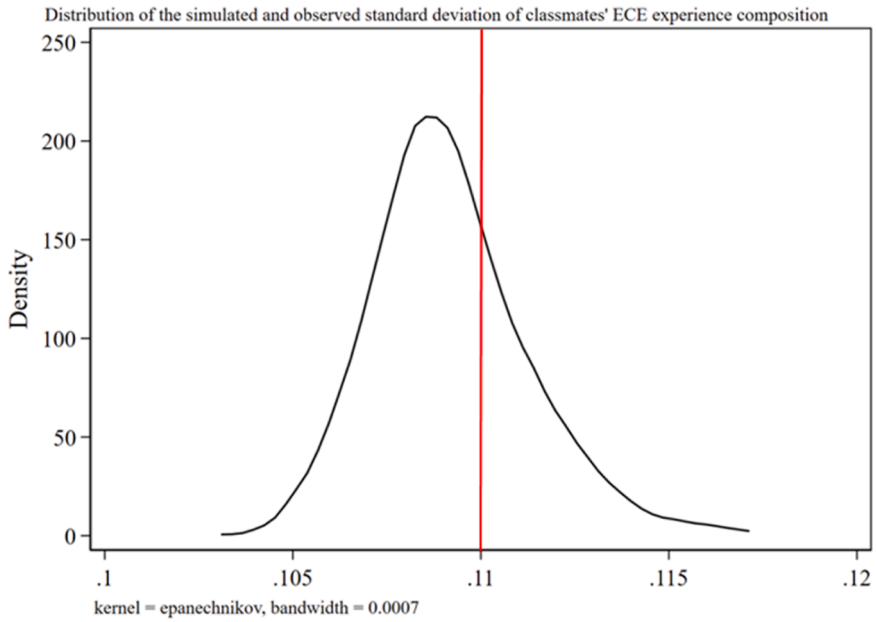

Fig. A.1. Distribution of the simulated and observed standard deviation of classmates' ECE experience composition in Grade 7. *Notes:* The black line depicted the distribution of the simulated standard deviation of the proportion of classmates with ECE experience which was calculated by randomly re-assigning sampled students to two classes within grade for 1000 times. The red line depicted the observed actual standard deviation of the proportion of classmates with ECE experience in our sample

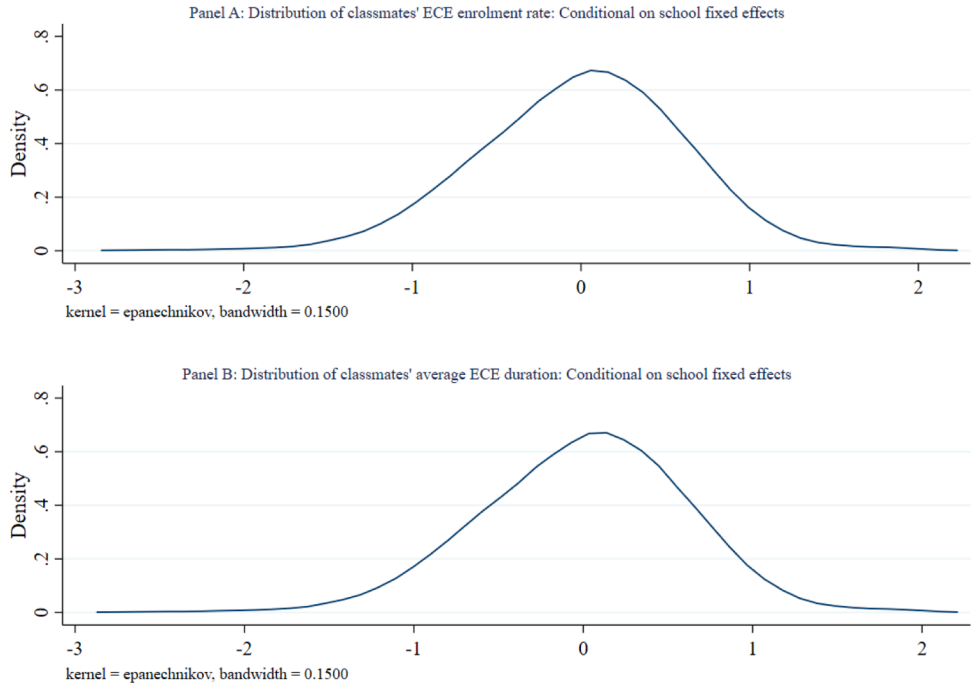

Fig. A.2. Distributions of classmates' ECE composition in Grade 7. ***Notes:*** The analyses reported in this figure are done at the class level. Panel A presents the conditional distribution of classmates' ECE enrolment rate in Grade 7, which is the distribution of residuals obtained from regressing classmates' ECE enrolment rate in Grade 7 on school fixed effects. Panel B presents the similar conditional distribution of classmates' average ECE duration in Grade 7

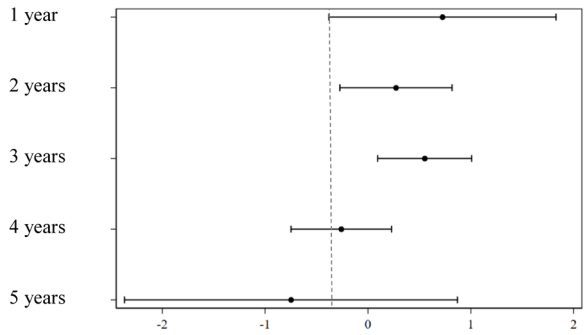

Fig. A.3. Non-linear effects of classmates' average ECE duration on cognitive abilities. ***Notes:*** Here we replace the continuous independent variable of classmates' average ECE duration with five dummy variables. Each dummy variable shows the proportion of classmates who attended 1, 2, 3, 4, or 5 years of ECE, respectively

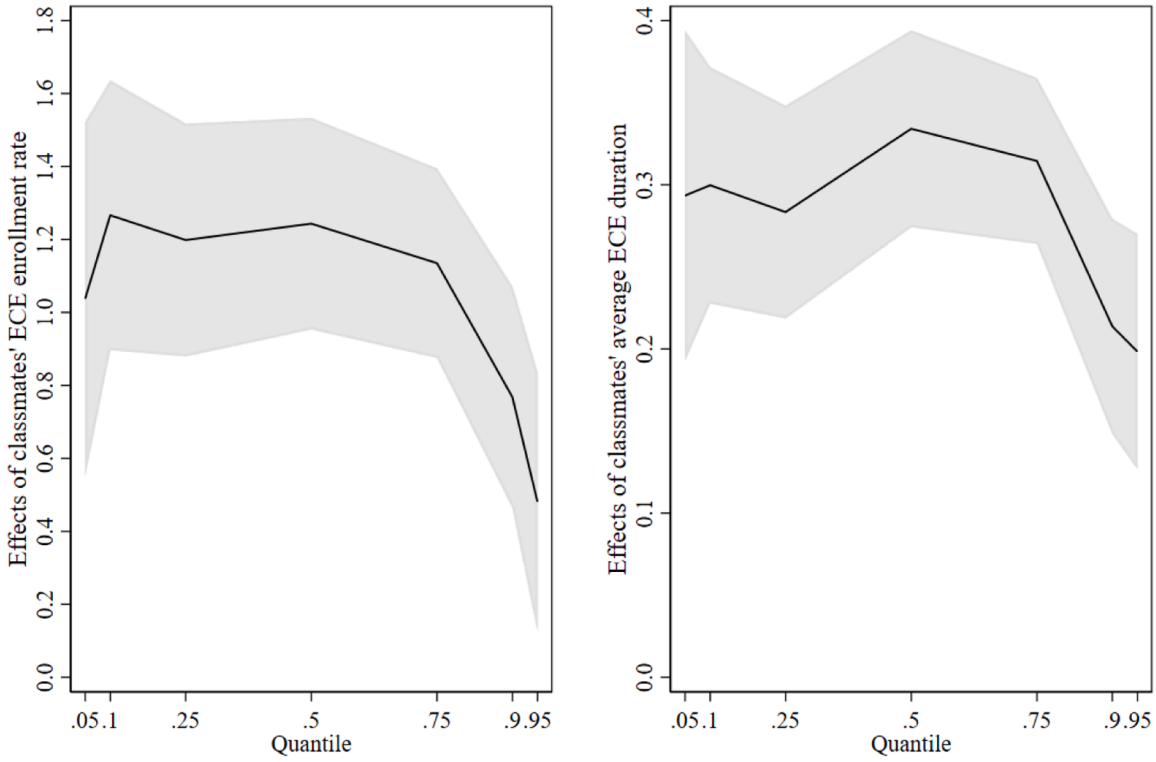

Fig. A.4. Quantile regression results. ***Notes:*** Here we replace the continuous independent variable of classmates' average ECE duration with five dummy variables. Each dummy variable shows the proportion of classmates who attended 1, 2, 3, 4, or 5 years of ECE, respectively

Table A.1
Balancing test for educational resources' allocation across classes within sample schools in Grade 7

	Average student age	Prop. of girls	Prop. of ethnic minorities	Average number of siblings	Prop. of students with ECE experience	Prop. of students being rural Hukou	Prop. of students from not poor family	Prop. of left behind children	Average years of schooling of fathers	Average years of schooling of mothers	Prop. of students' parents married
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Class size	−0.076	0.003**	0.003	−0.020**	0.006	−0.005	0.006	0.001	0.016	0.038	−0.001
	(0.102)	(0.001)	(0.003)	(0.008)	(0.006)	(0.007)	(0.011)	(0.007)	(0.035)	(0.045)	(0.002)
Age of head teacher	−0.088	−0.004	0.002	−0.004	0.007	−0.001	0.000	−0.007	0.021	0.011	−0.001
	(0.096)	(0.003)	(0.003)	(0.008)	(0.005)	(0.007)	(0.004)	(0.005)	(0.030)	(0.032)	(0.004)
Head teacher is male	0.898	0.006	−0.013	0.041	−0.015	0.060	−0.031	0.021	−0.342	−0.162	0.000
	(0.692)	(0.015)	(0.022)	(0.074)	(0.048)	(0.050)	(0.044)	(0.038)	(0.230)	(0.280)	(0.020)
Years of schooling of head teachers	−0.063	−0.001	−0.008	−0.016	−0.034*	−0.025	−0.004	0.011	0.024	0.129	−0.001
	(0.495)	(0.011)	(0.007)	(0.021)	(0.018)	(0.035)	(0.015)	(0.016)	(0.112)	(0.181)	(0.011)
Years of experience of head teachers	0.069	0.001	0.000	0.003	−0.003	0.001	−0.001	0.003	−0.012	−0.004	0.002
	(0.056)	(0.002)	(0.001)	(0.005)	(0.003)	(0.003)	(0.003)	(0.002)	(0.016)	(0.017)	(0.002)

(*continued on next page*)

Table A.1 (*continued*)

	Average student age	Prop. of girls	Prop. of ethnic minorities	Average number of siblings	Prop. of students with ECE experience	Prop. of students being rural Hukou	Prop. of students from not poor family	Prop. of left behind children	Average years of schooling of fathers	Average years of schooling of mothers	Prop. of students' parents married
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
School FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	174.0***	0.487**	0.018	1.802***	0.924***	1.074	0.696	0.243	9.302***	6.207*	0.978***
	(9.776)	(0.203)	(0.154)	(0.540)	(0.337)	(0.694)	(0.530)	(0.434)	(2.401)	(3.521)	(0.202)
N	104	104	104	104	104	104	104	104	104	104	104
R^2	0.960	0.901	0.978	0.954	0.795	0.949	0.860	0.596	0.960	0.958	0.652

Notes: (1) The analyses reported in this table are done at the class level. (2) Standard errors are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A.2
Measures of sample adolescents' non-cognitive ability and their raw scores (8th)

Item	Score	Mean	Std. Dev.
Social adaptation			
Feel bored at school	Strongly Agree = 1; Agree = 2; Disagree = 3; Strongly Disagree = 4	3.31	0.87
Have confidence in the future	Not confident at all = 1; Slightly confident = 2; Fairly confident = 3; Very confident = 4	3.16	0.71
Frequency of engaging in the following activities alone or with classmates:			
Visiting museums, zoos, science centers, etc.	Never = 1;	2.31	1.26
Going to movies, performances, sports events, etc.	Once a year = 2; Twice a year = 3; Monthly = 4; More than once a month = 5	2.67	1.43
Externalizing behaviors			
In the past year, have you engaged in the following behaviors:			
Swearing, using foul language	Never = 1;	2.14	0.99
Fighting	Occasionally = 2;	1.76	0.87
Bullying weaker classmates	Sometimes = 3;	1.12	0.49
Easily irritable	Often = 4;	1.82	0.99
Lack of attention	Always = 5	2.14	1.03
Skipping classes		1.08	0.43
Copying homework, cheating on exams		1.41	0.73
Smoking, drinking		1.1	0.47
Visiting internet cafes, arcades		1.16	0.58
Internalizing behaviors			
Do you have the following behaviors:			
I am very shy	Strongly Disagree = 1;	2.06	0.9
I often sit alone and prefer not to be with others	Disagree = 2;	1.81	0.91
When with classmates or peers, I rarely speak, mostly listening to them	Agree = 3; Strongly Agree = 4	1.96	0.95

Note: (1) The raw scores of measures of social adaptation, externalizing behaviors, and internalizing behaviors are measured in Grade 8. (2) In the following analyses, standardized scores for each measure are derived by averaging the raw scores of the sub-items and subsequently standardizing them.

Table A.3
Heterogeneous analyses by school characteristics

	Cognitive score (8th)	
	(1)	(2)
Panel A: by region		
	Urban	Rural
Classmates' ECE enrolment rate (7th)	0.646*	0.494
	(0.373)	(0.356)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	3248	695
R^2	0.384	0.593
Classmates' average ECE duration (7th)	0.092	0.017
	(0.087)	(0.061)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes

(*continued on next page*)

Table A.3 (*continued*)

	Cognitive score (8th)	
	(1)	(2)
N	3248	695
R^2	0.383	0.593
Panel B: by per-student funding		
	High	Low
Classmates' ECE enrolment rate (7th)	0.483	−0.094
	(0.459)	(0.666)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	2428	1692
R^2	0.504	0.467
Classmates' average ECE duration (7th)	0.025	−0.044
	(0.097)	(0.225)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	2428	1692
R^2	0.429	0.467
Panel C: by student-teacher ratio		
	High	Low
Classmates' ECE enrolment rate (7th)	0.557	0.158
	(0.548)	(0.392)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	2315	1805
R^2	0.408	0.494
Classmates' average ECE duration (7th)	0.127	−0.096
	(0.122)	(0.081)
Student CHs	Yes	Yes
Household CHs	Yes	Yes
Class CHs	Yes	Yes
School FE	Yes	Yes
N	2315	1805
R^2	0.408	0.494

Notes: (1) The region is defined by the type of area in which the school is located. Schools located in central urban areas, suburban areas, or urban-rural fringe zones are classified as urban, while those in towns or rural areas are classified as rural. The per-student funding refers to the amount of fiscal allocation per junior high school student in the current academic year. Schools at or above the sample median are classified as high; those below are classified as low. And the student-teacher ratio is measured by the number of students per teacher, with each teacher counted as one. Schools not lower than the median are classified as high, while those below are classified as low. (2) CHs stands for characteristics, FEs stands for fixed effects. (3) Student characteristics include cognitive score (Grade 7), age, gender, ethnicity, number of siblings, boarding status, and ECE experience of themselves. Household characteristics include hukou, years of schooling of both parents, parental marital status and at least one parent migration, family social economics status. Class characteristics include class size, head teacher' s age, gender, years of schooling, and teaching experience. (4) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A.4
Robustness check

	Cognitive score (8th)									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Classmates' ECE enrolment rate (7th)	0.707**	0.589*	0.600*	0.601*	0.572*					
	(0.303)	(0.323)	(0.306)	(0.306)	(0.321)					
Classmates' average ECE duration (7th)						0.085	0.063	0.067	0.068	0.059
						(0.081)	(0.071)	(0.070)	(0.070)	(0.072)
Classmates' proportion of being girls (%)	−0.853	−0.761	−0.718	−0.714	−0.716	−0.700	−0.609	−0.565	−0.561	−0.579
	(0.607)	(0.610)	(0.618)	(0.620)	(0.619)	(0.522)	(0.526)	(0.537)	(0.539)	(0.542)
Classmates' proportion of being the only child (%)		0.355	0.284	0.284	0.280		0.486*	0.420	0.420	0.403
		(0.315)	(0.327)	(0.327)	(0.326)		(0.281)	(0.320)	(0.321)	(0.317)
Fathers' years of schooling of classmates			0.022	0.022	0.015			0.021	0.021	0.008
			(0.046)	(0.046)	(0.047)			(0.046)	(0.046)	(0.047)
Mothers' years of schooling of classmates				−0.001	−0.001				−0.001	−0.001

(*continued on next page*)

Table A.4 (*continued*)

	Cognitive score (8th)									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
				(0.003)	(0.003)				(0.003)	(0.003)
Classmates' proportion of coming from rich families (%)					0.122					0.229
					(0.327)					(0.332)
Student CHs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household CHs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Class CHs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	4120	4120	4120	4120	4120	4120	4120	4120	4120	4120
R^2	0.452	0.453	0.453	0.453	0.453	0.450	0.452	0.452	0.452	0.452

Notes: (1) CHs stands for characteristics, FEs stands for fixed effects. (2) Student characteristics include cognitive score (Grade 7), age, gender, ethnicity, number of siblings, boarding status, and ECE experience of themselves. Household characteristics include hukou, years of schooling of both parents, parental marital status and at least one parent migration, family social economics status. Class characteristics include class size, head teacher' s age, gender, years of schooling, and teaching experience. (3) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A.5
Quantile regression results on the cognitive spillovers of classmates' ECE experience

	Cognitive scores (8th)						
	QR5 (1)	QR10 (2)	QR25 (3)	QR50 (4)	QR75 (5)	QR90 (6)	QR95 (7)
Panel A:							
Classmates' ECE enrolment rate (7th)	1.037***	1.266***	1.198***	1.243***	1.135***	0.768***	0.480***
	(0.247)	(0.188)	(0.163)	(0.148)	(0.132)	(0.154)	(0.181)
Student CHs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household CHs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Class CHs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	4120	4120	4120	4120	4120	4120	4120
Panel B:							
Classmates' average ECE duration (7th)	0.293***	0.300***	0.283***	0.334***	0.314***	0.214***	0.198***
	(0.051)	(0.037)	(0.033)	(0.031)	(0.026)	(0.033)	(0.036)
Student CHs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household CHs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Class CHs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	4120	4120	4120	4120	4120	4120	4120

Notes: (1) Columns (1) to (7) present the estimated results at the 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles of adolescents' cognitive ability in Grade 8. The lower the percentile, the higher their cognitive ability in Grade 8. (2) CHs stands for characteristics, FEs stands for fixed effects. (3) Student characteristics include cognitive score (Grade 7), age, gender, ethnicity, number of siblings, boarding status, and ECE experience of themselves. Household characteristics include hukou, years of schooling of both parents, parental marital status and at least one parent migration, family social economics status. Class characteristics include class size, head teacher' s age, gender, years of schooling, and teaching experience. (4) Standard errors reported in parentheses, clustered at the school level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

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