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Statistical learning as a buffer: Investigating its impact on the link between home environment and reading achievement

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ABSTRACT

The current study investigated the association between home environment and children's reading outcomes, with a focus on the mediating roles of vocabulary and morphological awareness (MA) and the moderating roles of statistical learning (SL). A sample of 191 8-year-old Chinese children (92 girls) with diverse socioeconomic status (SES) backgrounds completed assessments of vocabulary knowledge, MA, nonlinguistic visual and auditory SL, Chinese positional and phonetic SL, reading tasks, nonverbal reasoning, and verbal working memory. Results showed that both vocabulary and MA mediated the relationship between SES and reading, but only vocabulary mediated the relationship between home literacy environment (HLE) and reading. Importantly, children who were better in domain-specific SL, particularly those with strong Chinese radical positional SL, were less affected by SES disparities in reading outcomes. However, SL did not moderate the associations between HLE and reading outcomes.

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Introduction

Reading is one of the key achievements in education and is essential for functioning well in a developed society. Children's family environment is important in their reading development (e.g., Griffin & Morrison, 1997). Ample research evidence has demonstrated the links between children's reading achievement and various family factors, particularly its socioeconomic status (SES, a composite measure reflecting a family's economic and social position in relation to others based on factors such as income, education, and occupation; Bradley & Corwyn, 2002) (e.g., Liu et al., 2020; Romeo et al., 2022; Yeung et al., 2022) and home literacy environment (HLE, the quality and quantity of literacy-related resources and activities at home, including parental involvement in reading and availability of books and other literacy materials; Sénéchal & LeFevre, 2002) (e.g., Aram et al., 2013; Georgiou et al., 2021; Payne et al., 1994). Children growing up in lower-SES environments and with reduced home literacy experiences often achieve relatively lower reading levels (e.g., Buckingham et al., 2013; Pan et al., 2005; van Bergen et al., 2017). Moving beyond the mere negative effects of low SES and HLE, it is critical to identify potential protective factors. Indeed, recent research has shown that factors such as parental literacy involvement, child learning motivation, and child emotional status can protect against potential reading difficulties related to reduced SES and HLE (e.g., Chen et al., 2018; Hemmerechts et al., 2017). The current study extended attention to one intrinsic cognitive ability—statistical learning (SL)—to investigate its potential moderating role between family factors and reading achievement.

The link among SES, HLE, and reading

SES is an important influential factor in early literacy development (Bradley & Corwyn, 2002; Kieffer, 2010; see Romeo et al., 2020, for a review). Many studies have revealed moderate to high positive associations between SES and reading, with children living in lower-SES environments demonstrating lower reading achievement than their higher-SES peers (Buckingham et al., 2013; Sirin, 2005). SES remains to be a robust predictor of reading achievement throughout the school years, with *meta*-analyses showing that SES accounts for approximately 10% of variance in children's reading outcomes (Sirin, 2005; White, 1982).

Various developmental theories explain the link between SES and reading; for example, in ecological systems theory, Bronfenbrenner (1986) visualized the environment as layers of nested structures influencing development, with SES being a pivotal layer under the broad umbrella of environment. In addition, the family investment model (Conger & Donnellan, 2007) posits that parents with higher SES typically invest more resources and emotional support into their children's development compared with those with lower SES, and the rich resources and strong emotional support in turn affect children's overall learning and achievement. Given that SES is a multifaceted index of an individual's financial, educational, and social resources, there are presumably many ways in which SES may influence cognitive and academic development. The bioecological model of development (Bronfenbrenner & Ceci, 1994; Bronfenbrenner & Morris, 1998), built on the ecological systems theory, proposes that SES is a distal environmental factor that does not directly influence development but rather does so through proximal environments such as HLE, which refers to children's exposure to literacy-related resources at home, experiences with literacy activities, and parents' attitudes toward or beliefs about literacy and education in general. Indeed, ample research has revealed that HLE is associated with reading achievement, with better HLE facilitating reading development (e.g., Burgess et al., 2002; Georgiou et al., 2021).

Growing up in low-SES homes may affect reading achievement through multiple cognitive pathways. For example, in comparison with children with high SES, those growing up with low SES are likely to develop lower vocabulary knowledge, phonological awareness (PA, the ability to recognize and manipulate the sound structures of language; Adams, 1990), and morphological awareness (MA, the ability to recognize, understand, and manipulate morphemes; Carlisle, 2000) (Bowey, 1995; Schiff & Lotem, 2011; Schiff & Ravid, 2004). Indeed, both MA and vocabulary knowledge contribute directly to learning to read in Chinese. MA aids readers in decomposing characters into meaningful morphemes or radicals, facilitating character recognition and comprehension (e.g., Pan et al., 2016; Tong et al., 2017). Vocabulary knowledge provides the semantic base necessary to understand characters and compound words, helping readers to make connections between individual characters and words as well as high-level sentence and text comprehension (e.g., Pan et al., 2022; Yan et al., 2021). Together, MA enables decoding and comprehension of unfamiliar characters, whereas vocabulary supports comprehension of different levels of reading material, fostering fluent reading in Chinese.

Vocabulary knowledge and MA have been shown to be two important mediators in the relationship between SES and reading in Chinese and other languages (e.g., Cheng & Wu, 2017; Dolean et al., 2019). For example, Cheng and Wu (2017) showed that children from higher-SES families have better MA, which in turn contributes to an increase in their reading comprehension. In addition, Dolean et al. (2019) showed that the relationship between SES and reading outcomes was mediated by letter knowledge and phonemic awareness in English. Similarly, vocabulary knowledge and MA were shown to be two important mediators of the relationship between HLE and reading (e.g., Liu et al., 2023; Relyea et al., 2020) in languages such as Chinese and English after controlling for nonverbal intelligence and age (Liu et al., 2023). Taken together, MA and vocabulary knowledge both are considered important language skills in reading development (Liu et al., 2023).

The link between SL and reading

Human language and writing systems have rich and complex structures that enables children to induce statistical regularities from relatively noisy inputs, allowing them to encode a great number of probabilistic constraints embedded in their language and writing systems as a result of exposure and experience (Perruchet & Pacton, 2006). In a series of empirical studies (e.g., Arciuli & Simpson, 2012; Ren & Wang, 2023, 2024; Tong et al., 2020; von Koss Torkildsen et al., 2019; see Ren et al., 2023, for a *meta*-analysis), both domain-general (not limited to language; Frost et al., 2015) and domain-specific (within linguistic input; Conway & Christiansen, 2005) SL have been shown to link to early literacy-related outcomes.

Arciuli and Simpson (2012) used the classic triplet paradigm to test nonlinguistic visual SL and used the reading subtest of the Wide Range Achievement Test (WRAT-4; Wilkinson & Robertson, 2006) to assess children's ability to read aloud individually presented English orthographic strings. In the triplet paradigm, aliens were divided into four base triplets and were displayed on the computer screen one at a time in the familiarization phase. In the surprise test phase, four new triplets were created and children were prompted to identify which of the two (base or new) had appeared previously. A positive relationship was revealed between nonlinguistic visual SL and reading outcomes in children and adults. Furthermore, von Koss Torkildsen et al. (2019) used the same SL paradigm and showed that Norwegian school-aged children's performance on a nonlinguistic visual SL task predicted a unique amount of variance in real word reading efficiency in Norwegian, even after several other reading-related skills (e.g., expressive vocabulary, working memory) were taken into consideration. In addition, Qi et al. (2019) measured children's and adults' performance on nonlinguistic, nonlinguistic auditory SL (tone triplet paradigm), and nonlinguistic visual SL (classic triplet paradigm but with different stimuli) and their performance on real word, non-word, and sentence reading. Results showed that nonlinguistic auditory SL, but not nonlinguistic visual SL, was significantly associated with sentence reading fluency in the combined sample of children and adults (Qi et al., 2019). More recently, Ren and Wang (2024) revealed that, compared with auditory SL, visual SL contributed more to Chinese word reading. Given the potentially distinct roles that visual and auditory SL may play in reading, we included SL in these two modalities to comprehensively investigate their contribution to reading performance.

For domain-specific SL, some studies have revealed the effects of domain-specific SL in reading alphabetic writing systems (e.g., Conrad et al., 2013; Ise et al., 2014; Ren & Wang, 2023b; Ren & Wang, 2023c). In reading nonalphabetic writing systems, children with dyslexia were poorer at learning statistical patterns specific to Chinese orthography compared with their normal-achieving peers (Tong et al., 2020). In addition, both domain-general and domain-specific SL contributed to both first language (L1) Chinese and second language (L2) English reading (Ren & Wang, 2024). These studies together point to the important role of both domain-general and domain-specific SL in literacy across various writing systems.

Domain-specific SL: Orthographic regularities in Chinese writing system

The Chinese writing system provides a unique opportunity to study the domain-specific SL and its contribution to reading achievement. There are two essential kinds of orthographic regularities in Chinese. The first one is positional consistency, referring to how frequently a radical (a basic orthographic unit in Chinese) occurs in a given location within a compound character (composed of more than one radical) (Lui et al., 2010). The other one is phonetic consistency, referring to the consistency in orthography–phonology mapping by measuring the relative number of characters with the same pronunciation among those that share a phonetic radical (Lee et al., 2006). Most Chinese characters (>80%) are semantic–phonetic compounds containing a semantic radical that provides a cue to the meaning of the whole character and a phonetic radical that provides a cue to the pronunciation of the whole character (Shu et al., 2003). For example, the character 枝 (*branch*) /tʂɨ1/ consists of a semantic radical 木 (*wood*) indicating a wood-related concept and a phonetic radical 支 /tʂɨ1/ providing a cue to the pronunciation of the whole character. Moreover, radicals exhibit certain positional consistencies; semantic radicals are usually on the left or top position and phonetic radicals are on the right or bottom position in the left–right or top–bottom structured characters, respectively (Shu et al., 2003).

Previous research investigated SL of positional and phonetic consistencies in learning to read Chinese. Yin and McBride (2015) showed that native Chinese-speaking children are sensitive to visual–orthographic regularities before they receive formal literacy instruction in Chinese. Furthermore, He and Tong (2017) employed a modified classic SL paradigm (an artificial orthography learning task) in which a set of Chinese-like characters were created using an ideographic script (Dongba) and a syllabic script (Geba). After a short exposure to a subset of novel characters, children in Grades 3 to 5 (~8–10 years of age) were able to distinguish characters containing radicals in legal positions from those in illegal positions. It appears that children in late primary grades are able to detect statistical patterns in artificial characters without being taught explicitly. More recently, Ren and Wang (2024) demonstrated that Chinese visual SL significantly contributes to Chinese word reading, even after accounting for general cognitive ability. In addition, findings from a recent *meta*-analysis by Ren et al. (2023) showed that there is a moderate correlation between domain-specific SL and reading outcomes among children who read in their L1 or L2 across different age groups and experimental paradigms.

Potential moderation of SL on the relationships among SES, HLE, and reading

Although it is now well-established that SES, HLE, and SL contribute to reading, it is less clear whether SES, HLE, and SL would interact with each other to influence reading achievement. According to Bronfenbrenner’s (1979) ecological systems theory, development is shaped by both intrinsic factors (e.g., SL) and environmental factors (e.g., SES, HLE), suggesting that interactions between these domains are crucial for understanding complex skills like reading. It is possible that intrinsic pattern-learning abilities may mitigate the effect of environmental factors, such as SES and HLE, on language and reading outcomes. Indeed, recent evidence suggests that high SL buffers against the disadvantages in language development associated with low SES. Eghbalzad et al. (2021) measured event-related potentials in children aged 8 to 12 years while they performed a domain-general visual SL task. Children’s SL performance moderated the relationship between SES and both syntactic and vocabulary comprehension scores. For children demonstrating high SL, SES had a weaker effect on performance compared with children with low SL. Thus, it is possible that having better intrinsic pattern learning abilities could constitute a protective factor by reducing the effect of variation in language and literacy exposure. When children experience lower SES or HLE, those with strong SL ability may still be able to detect and extract the embedded regularities in language and writing systems essential for successful reading. However, children with lower SL ability may have a relatively weaker sensitivity to the regularities and need an enriched language and literacy environment. Studying this question is important because it can reveal potential factors that protect against less supportive family environment conditions, which in turn may have implications for effective intervention approaches.

The current study

We sought to examine the relationships among family environment, SL, language skills, and reading outcomes in typically developing 8-year-old children in China. At this age, children have received formal reading instruction in class for 2 years. We used the triplet SL paradigm (Qi et al., 2019) to measure domain-general SL. This triplet SL paradigm has been widely used in previous studies that examined the link between SL and reading (e.g., Arciuli & Simpson, 2012; Qi et al., 2019; von Koss Torkildsen et al., 2019). Domain-general SL includes both nonlinguistic visual and auditory SL, which support broad pattern recognition skills crucial for language learning. In contrast, domain-specific SL encompasses Chinese written language-specific skills, such as radical positional SL and phonetic SL, which are directly relevant to reading Chinese characters and understanding their structural (visual and phonological) regularities.

Our study was guided by three primary questions. First, would language skills (vocabulary knowledge and MA) mediate the link among SES, HLE, and reading outcomes? Second, would different types of SL moderate the direct link among SES, HLE, and reading outcomes after controlling for general cognitive abilities? Third, would different types of SL moderate the indirect path among SES, HLE, and reading outcomes after controlling for general cognitive abilities? Specifically, would different types of SL moderate the relationships among SES, HLE, and mediators or between mediators and reading outcomes? Our conceptual model is demonstrated in Fig. 1. Based on previous literature on the mediating role of language skills in reading (e.g., Cheng & Wu, 2017; Dolean et al., 2019; Liu et al., 2023), we hypothesized that the link among SES, HLE, and reading outcomes would be partially mediated by language skills. A direct path may also be present among SES, HLE, and reading in addition to the indirect path via language skills. We also hypothesized that SL may serve as a buffer against the impact of a disadvantaged family environment on reading outcomes. We proposed that this buffering effect

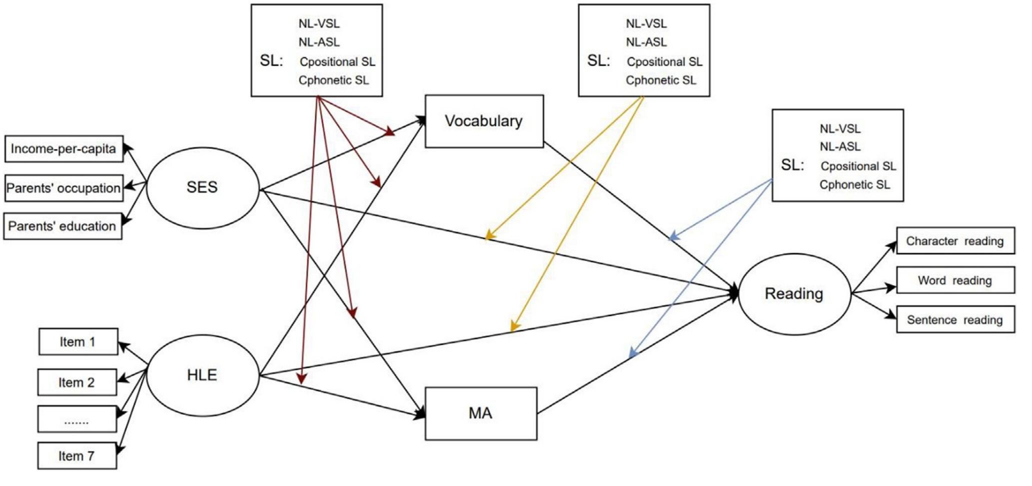


Fig. 1. Conceptual diagram representing the tested model and associated hypotheses. Hypothesis 1 addresses the mediation (SES → Vocabulary → Reading, SES → MA → Reading, HLE → Vocabulary → Reading, HLE → MA → Reading), Hypothesis 2 (denoted by yellow lines) addresses the moderation of the direct effect, and Hypothesis 3 (denoted by red lines, *a* path, and blue lines, *b* path) addresses the moderation of the indirect effect. Socioeconomic status (SES), home literacy environment (HLE), and reading outcomes are three latent variables. MA, morphological awareness; SL, statistical learning; NL-VSL, nonlinguistic visual SL; NL-ASL, nonlinguistic auditory SL; Cpositional-SL, Chinese positional SL; Cphonetic-SL, Chinese phonetic SL. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

would be shown in both direct and indirect links between family environment and reading outcomes. For the direct path, having better SL could help to reduce the effects of lower SES and HLE. Alternatively, it is possible that SL cannot compensate for variations in family environment. Furthermore, SL may moderate the mediation paths between family environment and reading outcomes. For children who have better SL abilities, the indirect links between family environment and reading via language skills may be significantly reduced compared with those who have weaker SL abilities. Finally, domain-specific SL may play a larger role in moderating both direct and indirect relationships between family environment and reading compared with domain-general SL.

Method

Participants

We recruited 191 typically developing second graders (M_{age} = 8.12 years, *SD* = 0.89; 92 girls) from two primary schools in rural areas in a small town near Yantai City, Shandong Province, China, where income inequality is much higher than in urban areas around Yantai (Wang, 2021). This town has been identified as a "poor county" since 2009 by the Yantai government. Children in the town received free milk during lunch. Whereas many children's parents live in the town, some parents live in smaller villages where families' SES is normally lower than that in the town. Our participants were native Mandarin-speaking children from families with varied SES backgrounds. All the children had normal or corrected-to-normal vision and hearing.

Measures

Family environment

The family environment questionnaire was modified from a well-established Chinese family environment assessment (Wang, 2021). A total of 26 items were created to reflect two aspects of family environment (i.e., family's SES and HLE). Similar questions have been used in previous studies in the Chinese context to reflect different aspects of family environment and have shown high factor loadings in latent structural analysis (Deng et al., 2015; Liu et al., 2018; Wang & Liu, 2021; Zhang et al., 2020). Family's SES was assessed with parental income, parental educational level, and parental occupation. The HLE was measured across three aspects: early home literacy activities, more recent home literacy activities, and access to print resources. The Cronbach's alpha coefficients for the three subscales in HLE are listed in Appendix B, and the full questionnaire is provided in Appendix A (see online supplementary material for Appendices A and B).

Domain-general SL

Nonlinguistic visual SL (VSL). This task was modeled after the triplet paradigm in Qi et al. (2019). There were 12 unique alien images divided into four groups of 3 images to create four base triplets (ABC, DEF, GHI, and JKL). For the test phase, four new triplets were created. The relative position of each image in a new triplet is the same as the base triplets, but the images were grouped into four new triplets (AEI, DHL, GKC, and JBF). Children would see and hear at the beginning, "Hi there, today you are going to see some aliens line up to enter a cool spaceship. We need you to help us keep track of a very special alien as the aliens line up to enter their spaceship. We will show you the alien now." In the familiarization phase, each of the four base triplets was repeated 24 times for a total of 96 triplets. Aliens were presented one at a time on a computer screen for 800 ms each with a 200-ms interstimulus interval (see Fig. 2). In the familiarization phase, children were instructed to press the spacebar as quickly as possible whenever the specific target alien appeared on the screen. The target alien image was always the third alien of one of the four base triplets. The test phase was introduced after the familiarization phase. On test trials, participants were asked to identify which of the two triplets (one was the base triplet and the other one was new) seemed more like what they had seen in the familiarization phase. There were 24 test items in total.

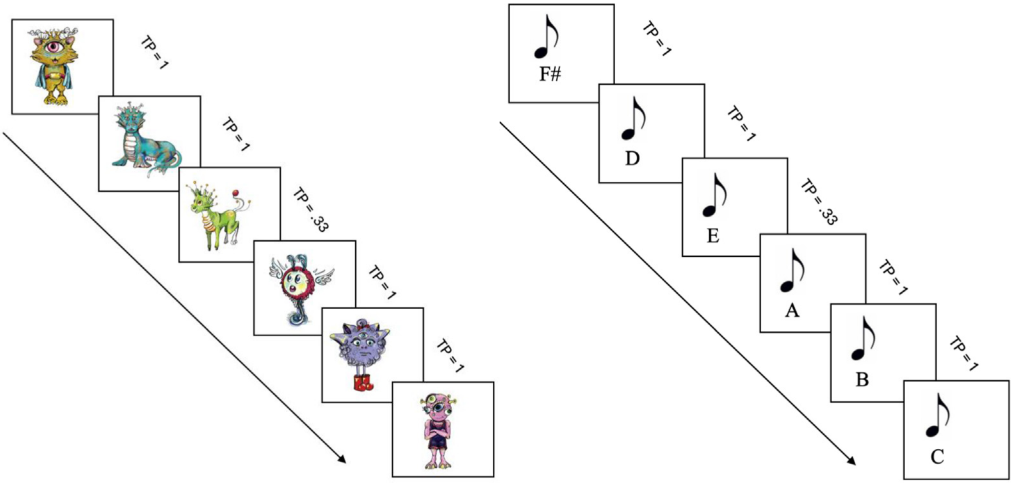


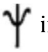
Fig. 2. Examples of statistical learning (SL) tasks in familiarization phase. Left: Visual SL paradigm example. Right: Auditory SL paradigm example. In a triplet paradiam, TP stands for transitional probability. TP=1: Predictable transitions between elements. TP=0.33: Less predictable transition (element followed by one of the three possibilities).

Nonlinguistic auditory SL (ASL). Modeled after Saffran et al. (1999), 12 pure tones within the same octave (a full chromatic scale starting from middle C) formed four base triplets (F#DE, ABC, C#A#F, and GD#G#). The new triplets were F#BF, AA#G#, C#D#E, and GDC. Children would see and hear at the beginning, "Hi! We're going to listen to some alien folk music today. We need you to help us keep track of a special sound as you hear different sounds." In the familiarization phase, each of the four triplets was repeated 48 times for a total of 192 triplets (twice as much as the visual conditions, following the standard paradigm). The duration of each tone was 460 ms with a 20-ms interstimulus interval (see Fig. 2). Children were instructed to press the spacebar as quickly as possible whenever they heard the target sound in the familiarization phase. The target sound was always the third one in one of the four base triplets. In the test phase, participants were asked to identify which of the two triplets seemed more like what they heard in the familiarization phase. There were 24 test items in total.

We used different repetition times for triplets in the familiarization phase to align with previous studies (Qi et al., 2019; Raviv & Arnon, 2018), ensuring that children received a roughly similar amount of exposure to both auditory and visual SL tasks. This approach accounts for the inherent differences in processing demands and sensory encoding between the two modalities; auditory stimuli have shorter durations and are processed more quickly, whereas visual stimuli are more complex and require additional time for children to fully process (Qi et al., 2019; Raviv & Arnon, 2018). By increasing the repetition times in the auditory SL task, we aimed to achieve comparable familiarity with the triplets across both modalities, minimizing modality-based performance discrepancies.

Domain-specific SL

Chinese radical positional SL. A modified positional statistical learning paradigm based on He and Tong (2017) and Tong et al. (2020) was employed by presenting participants with a stream of pseudocharacters, displayed one at a time in the center of the screen. For example, the target radical  occurred in its intended position (left) in all four pseudocharacters. If participants could detect the positional pattern of , then they would learn that  always occurs in the left position.

Participants were not informed of the learning goal for this task but were simply instructed to press the spacebar whenever two consecutively identical pseudocharacters appeared. In the formal learning phase, each of the 24 pseudocharacters was presented 20 times (24 × 20 = 480 trials) in a pseudorandomized sequence, with four instances of consecutive repetitions for each pseudocharacter, resulting in 96 (24 × 4) required responses for detecting repetitions. Participants' response accuracy was recorded to track their attention to the stimuli. The test phase asked participants which one of two characters looks more legitimate (e.g., a character with  in the left or a character with  in the right). There were 24 test items in total.

Chinese phonetic SL. This task was adapted from He and Tong (2017) and Tong et al. (2020). In the learning phase, a continuous stream of 400 learning trials (20 pairs × 20 repetitions) of pseudocharacter pairs (visual pseudocharacters and their pronunciations) were presented simultaneously in a fixed pseudorandomized order. For example, the sound "zén" was always associated with the radical , so the characters () all were pronounced as "zén.".

Children were asked to press the spacebar as quickly as possible whenever the same pseudocharacter-sound pair was repeated twice in a row. Following the learning phase, the recognition test started with 20 trials. Each test trial consisted of a pseudocharacter that had been previously displayed in the learning phase and, through headphones, a sequence of two sounds (i.e., one correct answer and one distractor). Participants were asked to select the sound paired with the pseudocharacter in the learning phase by pressing one of the assigned number keys on the keyboard. There were 24 test items in total.

Vocabulary knowledge

We employed a vocabulary definition task (Song et al., 2015) to measure vocabulary knowledge, adapted from the Stanford–Binet Intelligence Scale vocabulary subtest (Thorndike, 1986) for Mandarin-Chinese-speaking children. Children were orally presented with a word and asked to give a definition of it. There were 32 test items in total. For instance, the experimenters asked children, "What is a kitchen?" Scoring was based on the number of important semantic features included, following the scoring scheme in the test manual. Children were given 1 point for each feature, with a maximum score of 2 for each item. A complete definition needed to include the proper semantic category and one or more features.

General cognitive abilities

Raven's Progressive Matrices test (RPM; Raven & Raven, 2003) was used to assess *nonverbal reasoning*. Children completed a matrix by selecting a pattern to fit in among four different options, 24 items in total. The digit span backward task was used to assess *verbal working memory* (Wechsler Intelligence Scale for Children–Fourth Edition; Wechsler, 2003). Children repeated the numbers in the reverse order of what was presented by the tester. There were 4 trials for the list length of two and 2 trials each for the list lengths of three to eight. The test was stopped when children failed to repeat the 2 trials of the same length.

Reading outcomes in Chinese

Character reading. A character reading task was administered based on previous research (e.g., Shu et al., 2003; Yan et al., 2021). The 110 characters (e.g., 包 bag, 灯 lamp, 好 good) included 20 characters selected from the textbooks from each grade level (Grades 2–6) and another 10 characters not included in the textbooks (Elementary School Textbooks, 1996). The difficulty of the characters increased across the list. All participants were asked to read from the beginning and stopped when they failed to read 15 consecutive items. There was no time limit for this test. Only completely accurate pronunciation was given 1 point, with 120 total possible points.

Word reading. This test was modified based on a two-character Chinese word reading test (Liu et al., 2017) with 180 Chinese words in total. Children were asked to read aloud all the words (e.g., 我们 us, 老师 teacher, 太阳 sun) that were arranged in terms of difficulty and to skip any words that they could not read. No time limit was used for this test. If children failed to read 15 consecutive items, then the test was stopped. Only if children read both characters in a word correctly were they coded as correct. We coded how many Chinese words children read correctly.

Sentence reading fluency. A reading fluency task was based on Lei et al. (2011). It was a timed task, following the procedures of Moll et al. (2009). Children were given 3 min to read silently as many sentences as possible and judge whether the sentences were correct or not. There were 90 sentences (e.g., 天安门在北京 Tiananmen is in Beijing, 狮子不喜欢吃草 Lions don't like to eat grass, 长颈鹿脖子非常短 The giraffe's neck is very short), increasing in length across the sentences. The sum of characters in the sentences with correct responses in 3 min was calculated.

The above three reading measures were chosen to offer a comprehensive overview of reading skills at different levels: character, word, and sentence reading. Exploratory factorial analysis of these three measures revealed a single-factor solution that explained 89.26% of the total variance (eigenvalue = 3. 67). Thus, a single composite factor score was used in the following analyses.

Procedure

There were two sessions separated by 1 week. In Session 1, children completed nonlinguistic visual, nonlinguistic auditory SL, and the three reading tasks. In Session 2, children completed Chinese domain-specific positional and phonetic SL, the digit span, Raven, MA, and vocabulary tests. Half of the children were randomly assigned to Session 1 first, and the other half were assigned to Session 2 first. Within each session, half of the children completed SL tasks first, and the other half completed the other tasks first followed by SL tasks. Within the SL tasks, nonlinguistic visual was administered first and then nonlinguistic auditory SL, Chinese positional was first and then phonetic SL. The order of the three reading tasks was character, word, and sentence reading. The order of the remaining tasks was digit span, Raven, MA, and vocabulary. Parents were asked to complete the home environment questionnaire at the end of the first session.

Statistical analysis

We first reported descriptive statistics on family environment factors (family SES and HLE), language measures (vocabulary knowledge and MA), SL performance, reading measures (Chinese character, word, and sentence reading), and general cognition measures (nonverbal reasoning and verbal working memory). Before formal analysis, all the measures were standardized with a mean of 0 and a standard deviation of 1 to facilitate interpretation and comparison. Partial correlation analyses were also conducted to explore the relationships among these measures, controlling for age and gender.

We then constructed a series of structural equation models (SEMs) to test our three hypotheses. The measurement and structural models were specified with full information maximum likelihood estimation with robust standard errors to preserve all available data (Arbuckle, 1996). Model 1 was a basic model with the direct effect of family environment measures on reading without mediators or moderators. SES and HLE were allowed to covary, as were vocabulary and MA. Model 2 investigated the mediating role of vocabulary knowledge and MA in the relationship between family environment and reading outcomes, controlling general cognitive abilities. Models 3 to 6 investigated the moderating role of SL in the direct relationship between family environment and reading outcomes. Models 7 to 10 investigated the moderating role of SL in the indirect relationship between family environment and reading outcomes via language skills. To test indirect and direct effects of the variables included in all the SEMs, a 95% confidence interval was selected, and the bootstrap analysis was applied through 5000 resampling (Preacher & Hayes, 2008). Model fit indices, including the chi-square test statistic, comparative fit index (CFI), Tucker–Lewis index (TLI), root mean square error of approximation (RMSEA), and Akaike information criterion (AIC), were used to evaluate model fit. A model with a CFI value above.95, a TLI value above.95, and an RMSEA value below.06 is considered an excellent fit to the observed data (Hu & Bentler, 1999). A model with a CFI value above.90, a TLI value above.90, and an RMSEA value below.08 is considered an acceptable fit (McDonald & Marsh, 1990). All analyses were conducted using the "lavaan" package in R (Ihaka & Gentleman, 1996).

Results

Descriptive statistics about children's performance on all SL tasks, language measures, reading outcome measures, and general cognitive abilities tests are reported in Table 1. For the SES and HLE questionnaire, we report descriptive statistics in Appendix B.

Family's SES

The mean rating of average monthly household income on a 9-point Likert scale was 5.10 (*SD* = 2.31), indicating that the average monthly family income was close to 8,000 CNY. (Note that we selected the middle point of each category in the Likert scale as the average monthly income.) The average income-per-capita ratio was 2872.5 CNY per month. Based on Yantai Government Report (2023), the average household monthly income was 11,823 CNY and the average monthly income-per-capita in rural areas was 5113 CNY in 2023. This information suggests that the SES of the families in our study was lower than that of the average families in the broad Yantai area on both average monthly income and income per capita. On a 10-point Likert scale, the mean rating of father's educational level was 6.28 (*SD* = 1.39) and of mother's educational level was 5.19 (*SD* = 2.64), indicating that the average parental education was above technical secondary school education but below senior high school. On a 5-point Likert scale, the mean rating of father's occupational level was 3.12 (*SD* = 1.29), and of mother's occupational level was 2.14 (*SD* = 1.34), indicating that the average occupation level was close to low-level administrative type of work.

We ran a confirmatory factor analysis (CFA) including parental income, parental educational level, and parental occupation, yielding a unidimensional model with acceptable fit indices: χ^2/df = 1.47, CFI = .96, TLI = .93, RMSEA = .051, and factor loadings ranged from.612 to.798. Thus, a single composite factor score was used in the following analyses.

Home literacy environment

The mean rating of children's early HLE prior to schooling was 1.69 (*SD* = 0.34), meaning that parents less frequently engaged in literacy activities with children during their children's preschool years. The mean rating of children's current HLE experience was 2.37 (*SD* = 0.61), meaning that parents engaged in activities with children from once or twice every month to once or twice every week on average. The mean rating of access to print resources was 3.91 (*SD* = 1.23), meaning that the average number of books at home was around 50.

Table 1
Descriptive statistics of language, SL, reading, and controlled measures.

Measure	*M* (*SD*)	Range	Reliability (Cronbach's alpha)
Vocabulary	14.22 (6.07)	3–30	.89
Morphological awareness	16.25 (5.15)	4–24	.81
Nonlinguistic VSL	0.66 (0.14)	0.41–1	.71
Nonlinguistic ASL	0.60 (0.13)	0.36–1	.67
Chinese positional SL	0.71 (0.17)	0.33–1	.78
Chinese phonetic SL	0.74 (0.19)	0.33–1	.75
Character reading	84.57 (23.26)	22–120	.82
Word reading	148.02 (20.03)	117–180	.84
Sentence reading	32 (13.23)	16–67	.68
Nonverbal reasoning	18.54 (2.73)	13–23	.92
Verbal working memory	3.72 (2.06)	1–8	.71

Note. SL, statistical learning; VSL, visual SL; ASL, auditory SL. For SL tasks, we report accuracy rates. For vocabulary, morphological awareness, the three reading measures, nonverbal reasoning, and verbal working memory, we report the raw number of corrected items.

Based on our internal consistency analysis, home literacy activities (preschool), home literacy activities (current), and access to print resources scales all demonstrated high consistency, with Cronbach's alpha values of.91,.92, and.91, respectively. Given this high internal consistency, we averaged the items within each scale to create a composite score. These composite scores were standardized and included in a CFA with a unidimensional structure. Results showed that the model has a good fit, with χ^2/df = 2.19, CFI = .91, TLI = .90, and RMSEA = .061, with factor loadings of.602,.482, and.437, respectively, on home literacy activities (preschool), home literacy activities (current) and print resources scales. A single composite factor score was used in the following analyses.

Partial correlations among measures are reported in Table 2, controlling for age and gender. Children performed above chance (50%) in all four SL tasks (all *ps* < .05). Children's performance was significantly better in Chinese phonetic SL than in nonlinguistic VSL and nonlinguistic ASL (*ps* < .01). Children's performance in Chinese positional SL was significantly better than that in nonlinguistic ASL (*ps* < .01). There was no significant difference among other comparisons among the SL tasks. Table 2 shows that most SL tasks were correlated with each other, and most reading outcomes were correlated with each other. SES and HLE were correlated with most other measures. Only nonlinguistic ASL was significantly correlated with the two language measures. Vocabulary, but not MA, was significantly correlated with character and sentence reading. Nonlinguistic ASL, Chinese positional SL, and Chinese phonetic SL all were significantly correlated with two or three reading outcome measures.

Prior to performing SEMs, we removed outliers (±3 standard deviations) for each measure. First, an SEM (Model 1) was conducted to test whether family environment was directly associated with reading outcomes. Nonverbal reasoning and verbal working memory measures were included as control measures because they were correlated with all family factors and reading outcomes. The model fitted the data well (χ^2/df = 1.69, CFI = .95, TLI = .96, RMSEA = .05, AIC = 2321). SES significantly predicted reading outcomes (β = .466, *SE* = .102, *p* < .01), and HLE also significantly predicted reading (β = .512, *SE* = .224, *p* < .01). Among the two control variables, only nonverbal reasoning significantly predicted reading (β = .322, *SE* = .139, *p* < .01).

Do language skills mediate the relationship between family environment and reading outcomes?

The next SEM (Model 2; see Fig. 3) tested whether significant indirect effects were present from family factors to reading through language skills. Nonverbal reasoning and verbal working memory were included as controls. The model fitted the data well (χ^2/df = 2.16, CFI = .93, TLI = .92, RMSEA = .05, AIC = 2327). All the paths (except from HLE to MA) representing the indirect effects from SES to reading outcomes were significant (see Fig. 3). First, SES was significantly linked to vocabulary knowledge (β = .201, *SE* = .129, *p* = .003) and MA (β = .112, *SE* = .179, *p* = .007). HLE was significantly linked to vocabulary knowledge (β = .311, *SE* = .107, *p* < .001) but not to MA (β = .041, *SE* = .097, *p* = .319). Moreover, vocabulary and MA were significantly linked to reading outcomes (β = .223, *SE* = .107, *p* = .007 and β = .200, *SE* = .112, *p* = .005, respectively).

The indirect effects from SES to reading through vocabulary (β = .077, *SE* = .062, 95% confidence interval [CI] [.0645,.281]) and MA (β = .027, *SE* = .047, 95% CI [.021,.219]) both were significant. The indirect effect between HLE and reading through vocabulary was significant (β = .039, *SE* = .041, 95% CI [.014,.209]), but the indirect effect between HLE and reading through MA was not (β = .003, *SE* = .054, *p* = .212). The indirect effects between SES and reading through vocabulary and MA explained 13.21% and 19.12% of the total SES–reading relationship, respectively. The indirect effect between HLE and reading through vocabulary explained 11.2% of the total HLE–reading relationship. Moreover, the direct path from SES to reading remained significant (β = .101, *SE* = .101, *p* = .002), and the direct path from HLE to reading remained significant (β = .267, *SE* = .087, *p* < .001), indicating partial mediations. The two control variables were differentially associated with the mediators and reading outcomes. Children's nonverbal reasoning was associated with their vocabulary knowledge (β = .210, *SE* = .062, *p* = .003), MA (β = .316, *SE* = .099, *p* < .001), and reading (β = .113, *SE* = .091, *p* = .023) outcomes. Verbal working memory was not associated with any of the mediators or reading outcomes. The model explained 65.4% of the variance in reading.

Table 2
Partial correlations of all measures.

	SES	HLE	Vocabulary	MA	NL-VSL	NL-ASL	Cpositional-SL	Cphonetic-SL	Character reading	Word reading	Sentence reading	NR	VWM
SES	1	.58***	.21*	.17	.22*	.15	.23*	.28*	.31**	.18	.34**	.16	−.09
HLE		1	.33**	.3	.25*	.19	.22*	.28*	.45**	.18	.43**	.19	.11
Vocabulary			1	.22*	.10	.37**	.11	.42**	.52***	.08	.38**	.19	.04
MA				1	.16	.18	.07	.08	.05	−.09	.10	−.06	.09
NL-VSL					1	.18	.19	−.11	.09	.07	.11	.11	−.02
NL-ASL						1	.27*	.19	.35**	.10	.17	.04	.08
Cpositional-SL							1	−.06	.17	.3**	.08	.04	.10
Cphonetic-SL								1	.62***	.25**	.32**	.28**	−.08
Character reading									1	.28**	.45**	.62**	.20^{+}
Word reading										1	.20**	.08	.07
Sentence reading											1	.18	.11
Nonverbal reasoning												1	.37**
VWM													1

Note. Numbers in cells represent the Pearson product–moment correlation coefficients, controlling for participants' age and gender. Warm color represents positive and significant correlations, and cold color represents negative and significant correlations. Nonsignificant correlations were left blank. NL-VSL, nonlinguistic visual statistical learning; NL-ASL, nonlinguistic auditory statistical learning; Cpositional-SL, Chinese positional statistical learning; Cphonetic-SL, Chinese phonetic statistical learning; VWM = verbal working memory.

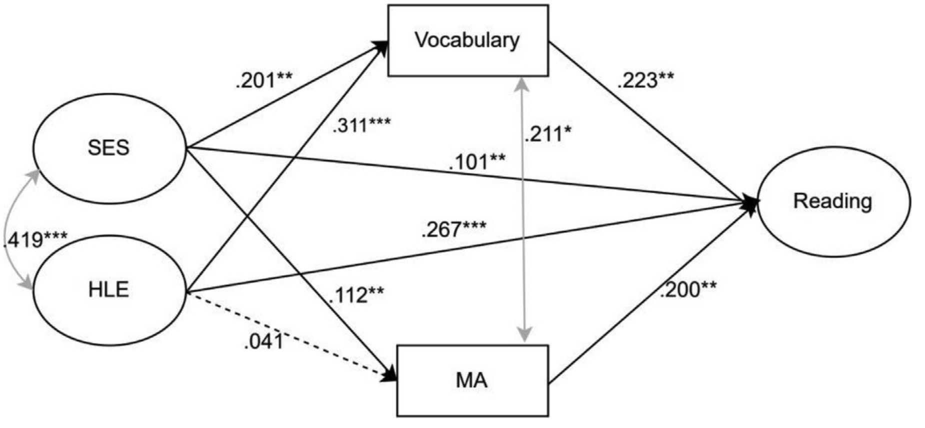


Fig. 3. Model 2: Structural equation model of language skills (vocabulary and MA) partially mediating the relationship between home environment (SES and HLE) and reading outcomes. MA, morphological awareness; SES, socioeconomic status; HLE, home literacy environment. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$. Numbers on pathways indicate standardized regression coefficients. Dotted lines indicate insignificant paths. Controlling variables (nonverbal reasoning and verbal working memory) are not shown in this figure for brevity. Gray lines denote correlations between two variables.

Do different types of SL moderate the direct link between family environment and reading outcomes?

We further constructed several separate models (Models 3–6) for each SL (Model 3: nonlinguistic VSL; Model 4: nonlinguistic ASL; Model 5: Chinese positional SL; Model 6: Chinese phonetic SL) to test whether different types of SL moderate the direct link between family environment and reading. Results showed that the moderating role of Chinese positional SL (Model 5) was significant between SES and reading ($\beta = -.088$, $SE = .101$, $p = .012$) (see Fig. 4), such that the direct link between SES and reading became non-significant ($p = .231$). This model explained 69.8% of the variance in reading. The

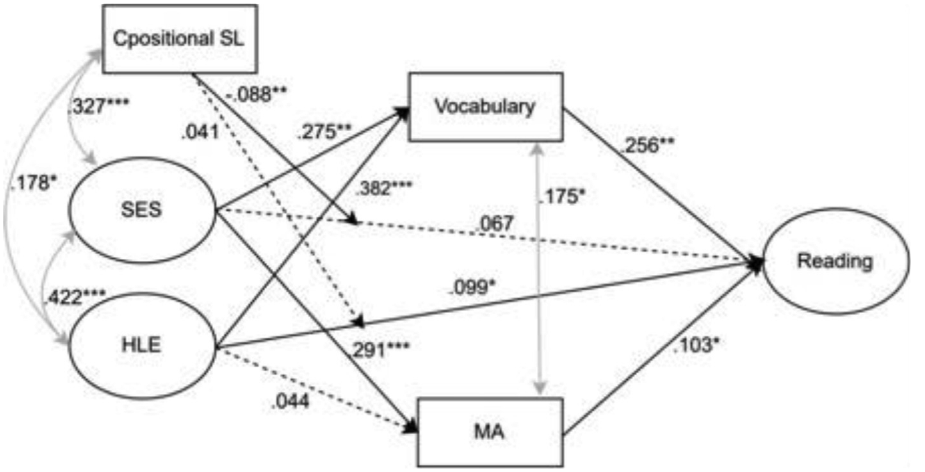


Fig. 4. Model 5: Chinese positional statistical learning (SL) as a moderator in the direct link between socioeconomic status (SES) and reading outcomes. Cpositional.SL, Chinese positional SL; HLE, home literacy environment; MA, morphological awareness. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$. Numbers on pathways indicate standardized regression coefficients. Dotted lines indicate insignificant paths. Controlling variables (nonverbal reasoning and verbal working memory) are not shown in this figure for brevity. Gray lines denote correlations between two variables.

moderating role of Chinese phonetic SL (Model 6) was significant between SES and reading ($\beta = -.099$, $SE = .098$, $p = .008$) (see Fig. 5), such that the direct link between SES and reading became nonsignificant ($p = .172$). This model explained 67.2% of the variance in reading. Further simple slope analysis (Fig. 6, left part) revealed that for children with low Chinese positional SL, SES was significantly associated with reading ($\beta = .182$, $SE = .131$, $p = .007$), such that the lower the family's SES, the weaker children's reading outcomes. However, for children with higher Chinese positional SL, the association between SES and reading was not significant ($\beta = -.029$, $SE = .078$, $p = .637$). A similar pattern was shown when Chinese phonetic SL served as a moderator (Fig. 6, right part). For children with lower Chinese phonetic SL, lower SES was associated with weaker reading outcomes ($\beta = .198$, $SE = .102$, $p = .005$), but for children with higher Chinese phonetic SL, this association was not significant ($\beta = .019$, $SE = .067$, $p = .581$). In both Models 5 and 6, neither SL measure moderated the direct effect of HLE on reading. In addition, the moderating roles of nonlinguistic VSL and nonlinguistic ASL on the direct paths between SES/HLE and reading (Models 3 and 4) were not significant. We further tested the strength of path coefficients between HLE and reading and between SES and reading. Results showed that the path coefficient from HLE to reading was significantly stronger than the path from SES to reading in Model 5 ($t = 2.45$, $p = .02$) and Model 6 ($t = 2.92$, $p < .01$).

Do different types of SL moderate the indirect link between family environment and reading outcomes?

We then tested whether different types of SL moderated the indirect paths from family environment to reading outcomes. Specifically, we tested whether each SL moderated the relationship between family environment and language skills and between language skills and reading outcomes. We constructed several separate models (Models 7– 10) for each SL (Model 7: nonlinguistic VSL; Model 8: nonlinguistic ASL; Model 9: Chinese positional SL; Model 10: Chinese phonetic SL). Model 9 revealed that Chinese positional SL moderated the effect of SES (but not HLE) on vocabulary ($\beta = -.112$, $SE = .101$, $p < .001$) (see Fig. 7) and MA ($\beta = -.107$, $SE = .073$, $p < .001$) (Fig. 7). Specifically, the moderated mediation analysis showed that the mediation was significant for children with lower positional SL (MA: $\beta = .037$, $SE = 0.034$, $p = .004$; vocabulary: $\beta = .024$, $SE = .028$, $p = .009$), but not for children with higher positional SL ($ps > .10$). Model 9 explained 71.1% of the variance in reading. No

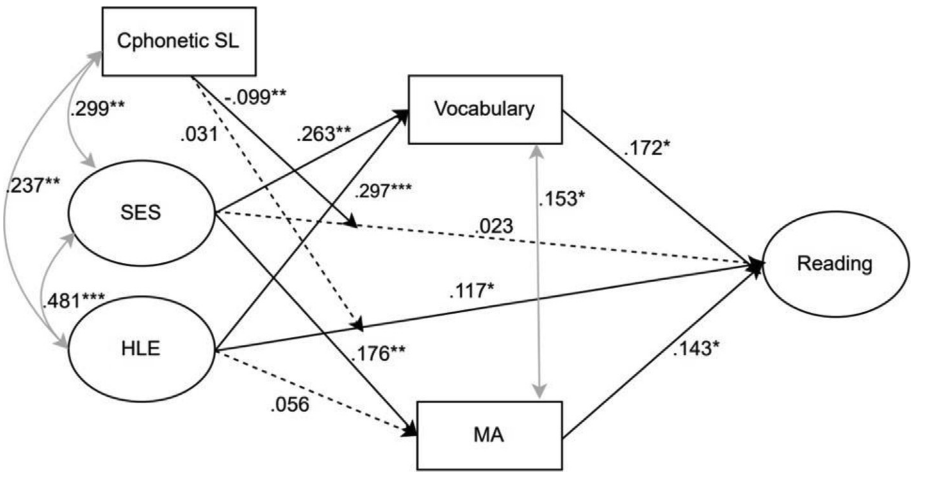


Fig. 5. Model 6: Chinese phonetic statistical learning (SL) as a moderator in the direct link between socioeconomic status (SES) and reading outcomes. Cphonetic.SL, Chinese phonetic SL; HLE, home literacy environment; MA, morphological awareness. *$p < .05$; **$p < .01$; ***$p < .001$. Numbers on pathways indicate standardized regression coefficients. Dotted lines indicate insignificant paths. Controlling variables (nonverbal reasoning and verbal working memory) are not shown in this figure for brevity. Gray lines denote correlations between two variables.

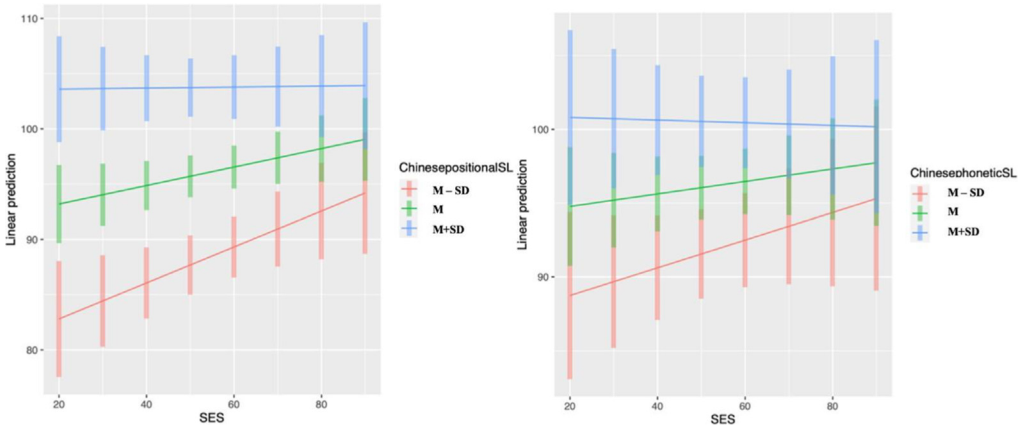


Fig. 6. Interaction between socioeconomic status (SES) and Chinese statistical learning (SL) on reading outcomes. Cpositional-SL, Chinese positional SL. The red line denotes SL performance below 1 *SD* (*M* – *SD*), the green line denotes SL performance at average, and the blue line denotes SL performance above 1 *SD* (*M* + *SD*). The y-axis indicates reading performance (composite score of character, word, and sentence reading). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

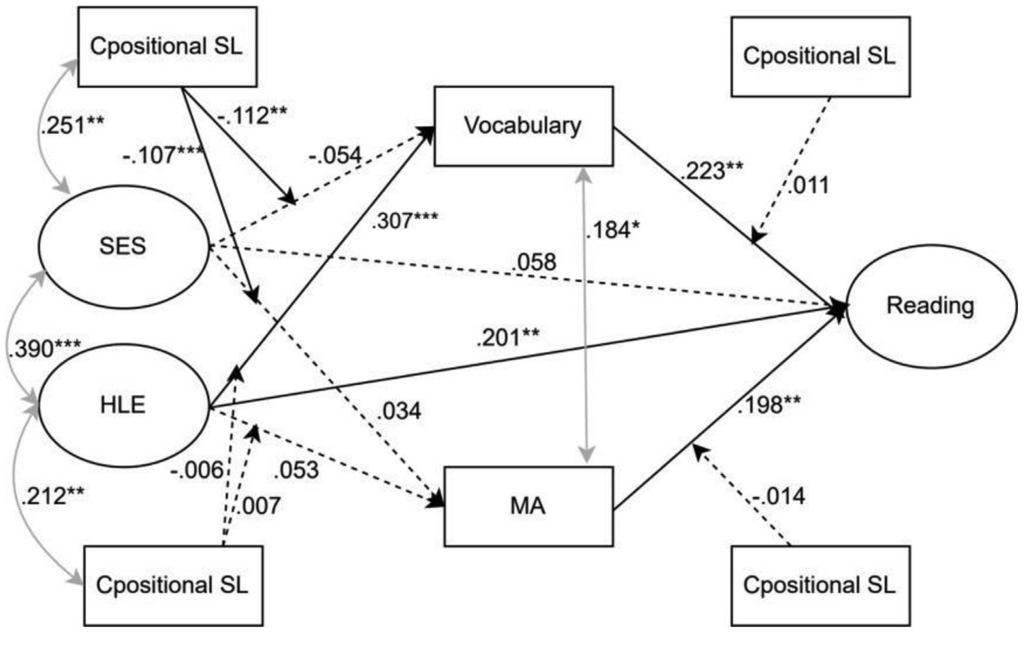


Fig. 7. Model 9: Chinese positional statistical learning (SL) as a moderator in the indirect link between socioeconomic status (SES) and reading skills. Cpositional.SL, Chinese positional SL; HLE, home literacy environment status; MA, morphological awareness. *$p < .05$; **$p < .01$; ***$p < .001$. Numbers on pathways indicate standardized regression coefficients. Dotted lines indicate insignificant paths. Controlling variables (nonverbal reasoning and verbal working memory) are not shown in this figure for brevity. Gray lines denote correlations between two variables.

other SL as a moderator was significant (Models 7, 8, and 10). The fit indices for all 10 models performed in the current analyses are listed in Appendix C of the supplementary material.

Discussion

Our study explored SL as a moderating factor that could mitigate the impact of family environment on reading development. By integrating both domain-general and domain-specific SL measures, it uniquely examined how various facets of SL interact with SES and HLE to influence reading outcomes, an area that has received limited attention in current research on reading development. Our findings revealed that language skills including vocabulary knowledge and MA significantly mediate the effects of family SES on reading. However, only vocabulary knowledge—not MA—mediates the relationship between HLE and reading. In addition, domain-specific SL (Chinese positional and Chinese phonetic SL) moderates the direct effect of SES on reading. Notably, for children with high SL, the association between SES and reading became nonsignificant, whereas it remained significant for children with lower SL. Furthermore, only Chinese positional SL moderates the indirect relationship between SES and reading via vocabulary and MA, showing that for children with better Chinese positional SL, the mediating roles of vocabulary knowledge and MA were not significant. Conversely, for children with weaker Chinese positional SL, the indirect pathways from SES to reading via vocabulary and MA were significant. These results seem to suggest that domain-specific SL may help to reduce the effects of a low-SES environment on reading both directly and indirectly by supporting language skills.

The relationships among SES, HLE, language skills, and reading

In line with previous research (e.g., Bowey, 1995; Cheng & Wu, 2017; Li et al., 2023; Schiff & Lotem, 2011; Schiff & Ravid, 2004), our results provide converging evidence that SES could both directly affect native Chinse-speaking children's reading outcomes and indirectly affect reading outcomes through children's vocabulary knowledge and MA. This finding may be explained by the ecological systems theory (Bronfenbrenner, 1986) and the family investment model (Conger & Donnellan, 2007). According to the ecological systems theory, sustained proximal environments such as family affect children's development directly, including their reading development. Higher-SES families may provide better financial, educational, and social capital to expose their children to quantitatively and qualitatively stronger learning environments, to foster more positive attitudes toward reading, and to seek better external resources to support their children's learning.

Our mediation paths are congruent with the proposition in previous research that higher family SES may facilitate language skills (vocabulary and MA) and in turn influence reading indirectly (Oakhill & Cain, 2012). Such mediation effects are in line with the investment theory of SES on academic learning (Yeung et al., 2022). That is, SES may play an important role in foundational language skills that are more proximal variables (e.g., vocabulary, MA) for reading development. On average, children from higher-SES families have a larger vocabulary size and are more aware of the word parts–morphemic units, which in turn relates to their better performance in reading. Broader and deeper vocabulary knowledge and MA provides a solid foundation for learning to read. Likewise, HLE, by providing children with increased exposure to language through activities such as reading together and storytelling, establishes a foundation for vocabulary development (e.g., Liu et al., 2023). This enhanced vocabulary in turn promotes lexical refinement and reading success. These findings align with previous research from other languages, further supporting the critical role of HLE in language and reading development. For instance, previous studies in English have demonstrated that HLE influences oral language skills such as vocabulary and morphological comprehension (e.g., Sénéchal et al., 2008). Moreover, vocabulary has long been recognized as a key predictor of both reading comprehension (e.g., Sénéchal et al., 2006) and word reading (Ouellette & Beers, 2010). These cross-linguistic findings together highlight the universal importance of HLE in shaping foundational language skills, which in turn contribute to reading success.

However, our results did not show the mediation role of MA in the link between HLE and reading. One possible explanation could be that the HLE measures used in our questionnaire heavily focused on informal, but not formal, literacy experiences. According to the home literacy model (Sénéchal, 2006; Sénéchal & LeFevre, 2002), informal literacy experiences are meaning-focused and expose children to print incidentally through activities such as shared book reading, which does not involve decoding practices essential for early reading development. Formal literacy experiences, on the other hand, are code- focused and expose children to print directly through activities such as teaching of basic letter–sound correspondences as well as advanced decoding skills. Previous studies have also shown that vocabulary, but not MA, mediates the effects of informal literacy experiences on reading (e.g., Manolitsis et al., 2013; Roth et al., 2002). The interpretation is that MA requires breaking words down into smaller units of meaning that informal literacy experiences usually cannot provide but may be provided by more formal literacy activities. Our results are in line with the previous findings and their interpretation.

Domain-specific SL moderates the direct link between SES and reading

Previous research has demonstrated that individual characteristics can serve as protective factors that moderate the association between SES risks and academic development. For example, Wang et al. (2017) showed that low affect, high effortful control, and low surgency could mitigate the associations between SES risks and children's reading and math development. Our findings revealed that an individual cognitive characteristic—domain-specific SL—could reduce the impact of low SES on reading. SL, broadly speaking, has been viewed as an intrinsic cognitive ability and shown to be related to a variety of language and reading outcomes. Individual performance on SL tasks has been shown to predict sentence comprehension among native English-speaking adults (Misyak & Christiansen, 2012), syntactic comprehension skills (Kidd & Arciuli, 2016), and lexical–phonological, lexical–semantic skills among native English-speaking children (Evans et al., 2009; Mainela-Arnold & Evans, 2014). Our study provided converging evidence that SL is associated with reading outcomes in Chinese across different materials (characters, words, and sentences).

Furthermore, we showed that high domain-specific SL benefits children from lower-SES backgrounds, but not necessarily children with lower HLE experience. There is a consensus in literature that reading development is highly dependent on both the environment in which children are raised and their own learning abilities (e.g., Estrera et al., 2023; Hart et al., 2013). Consequently, strong domain-specific SL may help children to mitigate the challenges associated with low SES. However, past evidence suggests that HLE is a more powerful predictor of reading outcomes than SES and has an impact on literacy achievement beyond what can be attributed to SES alone (e.g., Bracken & Fischel, 2008; Payne et al., 1994; Smith & Dixon, 1995). Our results also showed that HLE has a stronger direct influence on reading compared with SES. In Model 2 (Fig. 3), the path coefficients between HLE and reading are stronger than those between SES and reading.

Our research uncovered that only domain-specific SL (Chinese positional and phonetic SL) could mitigate the effects of low SES on reading, whereas nonlinguistic VSL and ASL did not show similar benefits. Chinese positional SL evaluates children's understanding of the spatial arrangement patterns of radical components within characters, a skill honed through implicit exposure to character reading and writing. Chinese phonetic SL assesses the ability to recognize consistent relationships between written characters and the pronunciation cues provided by phonetic radicals (He & Tong, 2017; Tong et al., 2020). Nonlinguistic VSL and ASL, on the other hand, gauge the capacity to detect patterns (transitional probabilities in the current study) in nonlinguistic visual and auditory stimuli, respectively. The domain-specific SL skills were shown to be closely linked to the acquisition of orthographic knowledge in Tong et al. (2020, 2023) and are strongly associated with reading performance encompassing character, word, and sentence reading in the current study. These findings may suggest that mere sensitivity to transitional probabilities in nonlinguistic contexts is less helpful in counteracting the impact of low SES on reading. Notably, in a study by Eghbalzad et al. (2021), the relationship between SES and language skills (syntactic and vocabulary knowledge) was moderated by children's nonlinguistic VSL. Eghbalzad et al. did not include any domain-specific (linguistic) SL measures. It is possible that nonlinguistic SL is associated with children's understanding of a language's grammatical structure and semantic knowledge of words. Given that their study did not include any reading outcome measures or domain-specific SL measures, we would not be able to know whether their nonlinguistic VSL would be associated with reading outcomes or whether any domain-specific SL would predict children's language skills. In the current study, better understanding of intricate orthographic-specific patterns, supported by domain-specific SL, emerges as crucial. Unlike the broader pattern recognition skills fostered by nonlinguistic SL, domain-specific SL in the Chinese reading context—particularly attuned to the unique radical positional and phonetic cues embedded in the Chinese writing system—plays a more critical role in navigating the complexities of Chinese orthography and thus supports reading development. Together, we argue that although nonlinguistic SL may contribute broadly to language development, the nuanced orthographic learning enabled by domain-specific SL is crucial for protecting children with low SES in reading development.

One notable finding of our study was the absence of a moderating effect of SL on the associations between HLE and reading outcomes. The lack of moderation of SL on the direct link between HLE and reading may suggest that a strong SL would not be able to mitigate the impact of a weak HLE on reading outcomes. One possible explanation could be that the mechanisms through which HLE supports reading development may operate through distinct pathways that are independent of SL abilities. For instance, HLE might predominantly influence reading outcomes by fostering specific language-related skills, such as vocabulary growth and print awareness, which are not directly tied to SL. This highlights the multifaceted nature of HLE and suggests that its role in reading development may extend beyond cognitive mechanisms associated with pattern recognition and statistical computations. For educational and intervention programs, it implies that enhancing HLE should prioritize activities that emphasize these foundational language and literacy skills rather than heavily targeting improvement in SL.

Chinese radical positional SL moderates the indirect link between SES and reading

Chinese radical positional SL also moderated the indirect paths between SES and reading via vocabulary knowledge and MA. Specifically, these indirect paths were significant only for children with low Chinese positional SL but not for children with high levels. Note that this significant moderated mediation is largely driven by the moderating role of Chinese positional SL on the relationship between SES and language skills, but not on the relationship between language skills and reading outcomes. In other words, children from low-SES environments with high positional SL may develop comparable language skills as their peers from higher-SES environments. Children with low positional SL, on the other hand, may show weak language skills associated with disadvantaged SES environments.

Moreover, a significant moderating effect of positional SL, but not phonetic SL, was shown on the indirect pathway from SES to reading. The difference across the two types of language-specific SL may stem from their differential roles in learning to read. In learning to read Chinese characters, the radical positional SL helps readers to become aware of the different components of the characters, which are associated with the semantic and phonetic radicals and their spatial locations within characters. The semantic radicals carry the meaning cues to the whole characters, which is directly relevant to the vocabulary knowledge measured in the current study and further contributes to the meaning understanding of the individual morphemes in compound words measured in our MA measure. The radical positional SL, vocabulary, and MA all are likely to rely on visual processing. The phonetic SL, on the other hand, heavily focuses on print-to-sound mapping, using the phonetic cues provided by the phonetic radicals in pronouncing the whole characters. Thus, we speculate that compared with positional SL, which is more likely related to semantic learning, phonetic SL is less likely to contribute to vocabulary and MA.

Our results support both Bronfenbrenner's (1979) ecological systems theory, which posits that development results from interaction between individual factors and environmental contexts. SL, an intrinsic cognitive ability, interacted with environmental factors (SES and HLE) in enhancing reading performance in our study. This finding showcased how the ecological context, together with cognitive abilities, influences reading achievement. This model provides a comprehensive framework for understanding how environmental, linguistic, and cognitive factors jointly contribute to reading development. Our study suggests that fostering domain-specific SL could be a valuable approach in developing reading intervention programs, particularly for children from lower-SES backgrounds. By integrating SL training into early literacy programs, educators could help children to develop stronger foundational skills such as SL to support reading development across diverse socioeconomic contexts, potentially mitigating some of the disadvantages associated with low SES at home. Our results showed that domain-general SL did not significantly moderate the effects of SES and HLE on reading and that domain-specific SL did not moderate the effect of HLE on reading. Drawing on theoretical frameworks and insights from Chinese reading instruction, we propose that these nonsignificant findings may reflect unique aspects of the Chinese language and literacy development. Unlike alphabetic writing systems, reading in Chinese heavily relies on character memorization and visual pattern recognition, which may limit the relevance of domain-general SL (such as nonlinguistic pattern learning) in supporting reading in this context. In addition, domain-specific SL may be less impactful in moderating the influence of HLE on reading given that HLE may primarily influence vocabulary acquisition and morphological awareness, which are critical to Chinese reading. These language-specific skills may overshadow the role of SL, particularly in young readers who rely heavily on direct instruction and repetition in their classroom curriculum.

Limitations and future directions

It is important to acknowledge some limitations that would potentially guide future research. First, the current study focused on concurrent relationships between family environment, language skills, SL, and reading outcomes. Future research needs to adopt a longitudinal approach to examine how these variables interact over time. Such a study could reveal whether the growth of language skills continues to mediate the link between family environment and reading outcomes and whether the growth (if any) of SL continuously moderates the direct and indirect relationships between them, depicting a more dynamic picture of their interaction. Second, our domain-specific SL tasks focused on two types of statistical regularities embedded in Chinese orthography: radical positional regularity and phonetic regularity. Future research needs to consider another important type of statistical regularities in Chinese orthography: semantic regularity. There is a variation in the degree to which semantic radicals convey the semantic cues to whole characters. It would be worthwhile for future research to test whether SL of semantic regularity is more likely to show strong links to vocabulary knowledge and MA. Third, the domain-general tasks in the current study assessed the ability to detect and learn transitional probabilities in sequences, whereas the domain-specific tasks assessed the ability to detect the specific orthographic regularities in Chinese focusing on the distributional probabilities of character component radicals. Hence, the two types of SL tasks tap into the different statistical properties. Caution is needed when interpreting the different patterns of moderating effects across different types of SL. Fourth, although our HLE measure reflects key components of the literacy environment at home, including preschool, current home literacy activities, and the accessibility to print materials, it might not fully encompass the multifaceted nature of HLE as defined in some literature covering parental beliefs and attitudes as well (e.g., Biggs et al., 2023; Justice et al., 2016). Finally, we recruited participants from rural areas in a small town with high income inequality to investigate how SL interacts with diverse socioeconomic backgrounds to affect reading skills. However, the specific socioeconomic and cultural characteristics of this community may limit the generalizability of our findings to other populations. Future studies should recruit participants across different communities, including urban settings, to enhance the generalizability.

Conclusions

The current study examined the relationships between family environment and children's reading outcomes, focusing on the mediating roles of vocabulary and MA and the moderating effects of domain-general and domain-specific SL. Both vocabulary and MA mediated the relationship between SES and reading, but only vocabulary mediated the relationship between HLE and reading, likely due to the fact that informal literacy experiences tapped in the HLE questionnaire might not directly support MA. Importantly, our results showed that children who are better in domain-specific SL, particularly children with strong Chinese radical positional SL, were less affected by SES disparities. Orthographic-specific SL may mitigate the effects of lower SES on reading development, supporting the crucial contribution of orthographic learning to successful reading. However, neither nonlinguistic nor Chinese-specific SL significantly moderated the relationship between HLE and reading. Our study provides initial evidence regarding the potential role of orthographic-specific SL as a buffer against the impact of SES disparity on reading achievement.

CRediT authorship contribution statement

Jinglei Ren: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Min Wang:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Xianglin Zhang:** Writing – review & editing, Validation, Methodology. **Rachel Romeo:** Writing – review & editing, Supervision, Methodology. **Joanne Arciuli:** Writing – review & editing, Supervision.

Data availability

Data will be made available on request.

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Data availability

The analyses presented here were not preregistered. The data, analytic code, and materials necessary to reproduce the analyses presented here are not publicly accessible. Data, code, and materials are available upon reasonable request to the corresponding author.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2025.106201.

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