# A DIMENSIONAL PERSPECTIVE ON THE HOME ENVIRONMENT AND NEUROCOGNITIVE SYSTEMS IN CHILDREN'S READING DEVELOPMENT

By

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# DEDICATION

This work is dedicated to the children who have yet to fully realize their potentials that the future holds; to the families who persevere through hardship and circumstantial headwinds for their loved ones; and to the community members who plants trees knowing that only the next generations will enjoy the shade. This work is especially dedicated to my *Bà Nội* (paternal grandmother), *Vũ Thị Kim Ơn*, for showing me your love for our family and care for our neighbors, "no matter how poor we are, as long as we have each other;" my *Mẹ* (mother), *Nguyễn Thị Kiều Trang*, for showing me work ethics, tenacity, and trustworthiness in life, as well as how life could be molded with dedicated hands and a flexible mind; my *Ba* (father), *Nguyễn Quang Trung*, for showing me patience, humility, and curiosity, as well as how outcomes are linked to efforts, sacrifices, and understanding; my *Em Trai* (younger brother), *Nguyễn Quang Nghĩa*, for showing me enthusiasm and love towards the little things in life, as well as for your acceptance and big-brother-ness; and my partner, *Rodney N. Killion*, for showing me devotion to our loved ones, your earnestness, brilliance, and gentle heart, and for being my everything and my better half. This is to my loved ones, birth family, dear friends, and chosen family, as well as everyone with whom I have had the pleasure of meeting and connecting – thank you for sharing your life, stories, and kindness.

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| | |
|---|---|
| HLE | Home literacy environment |
| SES | Socioeconomic status |
| RC | Reading comprehension |
| WR | Word recognition |
| OL | Oral language |
| EF | Executive function |
| WASI | Weschler Abbreviated Scale of Intelligence |
| ARHQ | Adult Reading History Questionnaire |
| WJ | Woodcock-Johnson |
| TOWRE | Test of Word Reading Efficiency |
| TOWK | Test of Word Knowledge |
| NEPSY | Neuropsychological Assessment |
| WMTB | Working Memory Testing Battery |
| GMRT | Gates-MacGinite Reading Tests |
| ESS | Extended Scale Score |
| CFI | Comparative fit index |
| TLI | Tucker-Lewis index |
| RMSEA | Root mean square error of approximation |
| SRMR | Standardized root mean squared |

# CHAPTER 1

## Introduction: Individual differences in reading development

### Motivation

Learning how to read is an important milestone in middle childhood. Children's reading outcomes are key to future educational attainment, vocational and occupational pursuits, and other adult functioning (Ritchie & Bates, 2013). While reading instruction primarily takes place in school (Castles et al., 2018), the home environment has been cited as a strong influence on children's school readiness and, in turn, reading outcomes (Bradley et al., 1988; Wirth et al., 2022). Being able to read allows children to fully appreciate the written materials that that they encounter throughout their education, as well as prepare for future vocational pursuits and post-graduate education that have high literacy demands (Gottfried et al., 2015). Moreover, literacy skills are apparent and necessary in everyday functioning for individuals to sustain their well-being, including reading the news, prescription labels, and financial documents (Nguyen et al., 2022; Welcome & Meza, 2019). Links between the early home environment and children's academic outcomes and eventual adulthood functioning make the influence of the home factors an attractive target to evaluate in terms of neurocognitive development.

Understanding precisely how the home environment impacts children's reading development needs further work. This chapter starts by laying the theoretical groundwork for a model to analyze the link between the home environment and reading development as follows:

- First, we review what is known in the literature regarding the cognitive and neural correlates of reading, thus mapping out the potential neuro-cognitive mechanisms that could explain home influences on outcomes.
- Then, we survey what studies have revealed thus far about co-occurring factors in the home environment that make a meaningful contribution to children's reading development.
- Next, we unite these findings to outline specific hypotheses concerning factors in the home environment, indices of neurocognitive systems, and children's reading outcomes.
- Finally, we describe different ways to test these specific hypotheses using a combination of behavioral measures and brain imaging approaches.

# Neurocognitive architecture of reading

Reading is complex. To read, individuals must decode written words and implement background knowledge to derive meanings, while connecting different ideas and maintaining a mental model to support comprehension and the making of inferences (Y.-S. G. Kim, 2020). Thus, individual differences in reading outcomes can arise from many sources – some of which can be observed through behavioral measures (Peng et al., 2022) or analyzed at the brain-systems level (C. J. Price, 2012). Below is an overview of reading by focusing on the importance of word recognition skills, and then a survey of how individual differences in reading development are influenced by other neurocognitive systems, including language comprehension and executive functions.

## Word recognition skills and the brain reading network

Learning to read requires explicit teaching, with the most common focus of instruction and intervention lessons placed on developing visual word recognition (WR; or decoding) skills. Lessons on decoding skills expose children to fast and efficient mapping between word-forms and speech-sounds of visual words – or phonics instruction (Castles et al., 2018; Melby-Lervåg et al., 2012). The reason for this focus is because inefficient WR creates a bottleneck that limits children from accessing meaning beyond the written codes (LaBerge & Samuels, 1974). Put simply, if children are not able to read, they are not able to understand – or achieve reading comprehension (RC), which is the endpoint in reading development (Stuart & Coltheart, 1988). Children are expected to have mastered and developed automatic WR skills by the end of second grade, as thereafter they are supposed to be able to read long and complicated texts (e.g., informational and non-fiction literature) that place demands on top-down cognitive systems (Fuchs et al., 2001; Hudson et al., 2008; Y.-S. G. Kim et al., 2020; Klauda & Guthrie, 2008). Laborious reading limits children from making use of high-level cognition and can render the reading task itself unfruitful, unproductive, and unenjoyable (McKenna et al., 1995).

Brain imaging studies have revealed that reading in part relies on the left-lateralized occipital-temporal cortex, which lies at the juncture between the visual (occipital) and auditory (temporal) systems (McCandliss et al., 2003; Saygin et al., 2016; Schlaggar & McCandliss, 2007). The occipital-temporal cortex within the ventral visual stream appears to be involved at both levels of WR and RC (Aboud et al., 2016; Ozernov-Palchik et al., 2021), thus highlighting a core node in the brain reading network. Studies have revealed additional recruitment of the inferior frontal gyrus and superior temporal gyrus that are implicated in lexico-semantic functions and auditory perception (Joseph et al., 2001; Turkeltaub et al., 2002). These findings highlight the importance of rudimentary visual-auditory neurocognitive abilities in children's reading outcomes, while also supporting the argument that reading skills co-opt the brain's visual system to implement an input pathway into the existing language network (Fiez & Petersen, 1998; Pugh et al., 2001; Yeatman et al., 2013).

Although to a lesser extent, imaging studies have reported the involvement of the right occipital-temporal cortex in reading (Blau et al., 2010; Booth et al., 2003; Hoeft, Meyler, et al., 2007; Nugiel et al., 2019). The interpretations for why the right occipital-temporal cortex may be involved in reading are also mixed: some reports suspect a neural compensatory mechanism in reading (Hoeft, Meyler, et al., 2007; Hoeft, Ueno, et al., 2007), while others posit a developmental tuning effect of the occipital-temporal cortex to relevant stimuli (Booth et al., 2003; Centanni et al., 2017; Church et al., 2008). In particular, some reports have analyzed activity patterns during in-scanner reading tasks between typical readers versus peers with reading difficulties (Hoeft, Meyler, et al., 2007; Nugiel et al., 2019). Reading difficulties appear to be linked to differences in the right occipital-temporal gyrus, as well as the right inferior frontal gyrus (Farris et al., 2011; Hoeft, Meyler, et al., 2007; Nugiel et al., 2019). The involvement of these right-hemisphere regions was interpreted as a neural compensatory mechanism in reading processes (Hoeft, Meyler, et al., 2007; Nugiel et al., 2019). On the other hand, the involvement of the right occipital-temporal cortex could just reflect some general visual processes that may be relevant to the early stages of reading development (Finkbeiner et al., 2006; Woodhead et al., 2011). Using reading and rhyming tasks, one study has found activity in the bilateral occipital-temporal cortices during both tasks in children, but only during the reading task in adults (Church et al., 2008). Comparing between lexical processing tasks, another study has shown that adults exhibit activation in the occipital-temporal cortex for visual word forms, while children do not (Booth et al., 2003). These findings suggest that the acquisition of reading skills may transiently utilize visual processes supported by the right hemisphere prior to becoming dependent on the left-lateralized occipital-temporal correlates (Booth et al., 2003; Centanni et al., 2017; Church et al., 2008).

## Language and executive functions: Neural systems and reading

Beyond the bottom-up decoding skills, reading development has been linked to top-down neurocognitive functions, including oral language and executive abilities. The involvement of language in reading development is not at all surprising because of their shared verbal system and processes (Dickinson et al., 2010). The *Simple View of Reading* argues that RC performance is the product of word decoding and language comprehension abilities (Hoover & Gough, 1990). Decades of findings as well as several meta-analyses have clearly shown the relations between language indices, decoding skills, and RC outcomes (Cutting & Scarborough, 2006; Keenan et al., 2008; Kendeou et al., 2009; Quinn & Wagner, 2018; Spencer & Wagner, 2018). Parallel findings argue that reading development is linked to fundamental cognitive processes, such as executive abilities (Butterfuss & Kendeou, 2018; Follmer, 2018). Indices of children's language and executive abilities have been reported to share a substantial amount of overlapping variance, perhaps illustrating how intertwined these processes are (Romeo et al., 2022; Weiland et al., 2014). Some studies have taken a neurobiologically motivated approach to "layer" the involvement of top-down language and executive abilities in reading, aiming to distinguish their direct versus mediated effects. With the use of path modeling strategies, emerging data from this line of research suggest that executive abilities operate through decoding skills and language abilities to facilitate RC performance (Y.-S. G. Kim, 2020; Spencer et al., 2020). Yet, much more remains to be understood in terms of how language and executive abilities and their underlying neural systems relate to children's reading outcomes.

### ***Language comprehension and the brain language system***

Oral language (OL) comprehension is well known to be foundational for children's reading development (Dickinson et al., 2010). One set of evidence comes from developmental studies that show a linkage between oral vocabulary and awareness of phoneme-grapheme correspondence (Deacon, 2012; G. Ouellette & Beers, 2010). Vocabulary knowledge is thought support children's sensitivity to speech-sounds units and how they relate to word meanings, as well as awareness of word-forms to develop fully detailed representations of words and facilitate rapid decoding (G. P. Ouellette, 2006; Roth et al., 2002; Seidenberg & McClelland, 1989). These findings have motivated the consideration of vocabulary knowledge as one school readiness metric, along with emergent literacy abilities, all of which are key for developing reading skills (Hjetland et al., 2020; Storch & Whitehurst, 2002; Whitehurst & Lonigan, 1998). Theoretically, these findings align with the *Lexical Quality Hypothesis*, which argues that the quality of semantic representations aids children in fast mapping of visual words that are accessible via their mental lexicon (Perfetti & Hart, 2002).

As children advance to the "reading to learn" stage and beyond, the demand on high-level OL functions becomes increasingly apparent (Dolean et al., 2021; Lervåg et al., 2018; Oakhill & Cain, 2012; Verhoeven & van Leeuwe, 2008). In-depth analyses have revealed that after accounting for core decoding and foundational OL skills (vocabulary and grammar), RC builds on successful listening comprehension that is achieved via developing an accurate mental model of the text (M. A. Barnes et al., 2014, 2015; Y.-S. G. Kim, 2020). These findings are theoretically supported by the *Construction-Integration Model*, which asserts that word-level abilities and top-down cognition interact in ways that enable the child to simulate a mental model of the text and, in turn, understand (Kintsch, 1991).

Neurobiological studies have revealed that comprehension is supported by the temporal-parietal network. Reading words in sentential context appears to tap overlapping yet more widespread areas compared to those found during single word decoding, including the inferior frontal and middle-superior temporal gyri (Cutting et al., 2006; Just et al., 1996). Larger clusters of lateral temporal areas, including the temporal pole and inferior temporal gyrus, have also been implicated in sentence comprehension and may be unique to those areas activated by single words alone (Walenski et al., 2019). These brain areas are thought to support verbal storage, semantic spreading, and syntactic integration, all of which are known to support RC (Friederici, 2002, 2011).

Beyond the word and sentence levels, reading appears to recruit brain regions implicated in discourse processing (Aboud et al., 2016; Moss et al., 2011). One particularly important finding is the involvement of the angular gyrus, which is situated in the inferior parietal lobule, adjacent to the supramarginal gyrus that supports phonological perception, and neighboring the temporal-parietal junction that underlies social cognition (Spreng & Andrews-Hanna, 2015). The angular gyrus is thought to guide the verbal memory, semantic representation, and conceptual integration needed for RC (Mar, 2011). This is likely due to the angular gyrus' dense connections with multiple cortical areas (i.e., it is a *hub* region) and heteromodal nature (Seghier, 2013; Sydnor et al., 2021; Tooley et al., 2022). Moreover, RC performance has been shown to evoke activity in the posterior cingulate cortex, which is thought to facilitate mentalizing and contextualization processes in discourse cognition (Aboud et al., 2019; Ferstl et al., 2008; Jacoby & Fedorenko, 2020).

### *Executive functions and the brain prefrontal system*

Implementing individual or multiple reading and language processes in RC is thought to tax foundational cognitive resources; thus, it is not surprising that executive functions (EFs) have been implicated in RC. Central EFs include working memory, cognitive flexibility, and inhibitory control, which are subserved by regions in the prefrontal cortex (A. Diamond, 2013; Friedman & Miyake, 2017; Miyake et al., 2000; Zelazo & Carlson, 2012). Behavioral studies have shown that children's performance on EF measures predict differences in their reading outcomes, even when accounting for WR and OL processes (Butterfuss & Kendeou, 2018; Cutting et al., 2009; Follmer, 2018; Sesma et al., 2009). EFs are hypothesized to play a role in RC by coordinating WR skills and OL abilities (Butterfuss & Kendeou, 2018; Moss et al., 2011; Nouwens et al., 2021). Studies have revealed that accounting for WR and OL processes reduces the associations between EF measures and RC performance (Peng et al., 2018), suggesting that the link between EFs and reading outcomes involves the *Simple View of Reading* components.

There are several ways that EFs may operate through WR and OL processes to influence reading outcomes. For instance, visual WR is thought to tap working memory to store and process phonological-orthographic inputs (Baddeley & Hitch, 1974; Seigneuric & Ehrlich, 2005). Cognitive flexibility is thought to be involved in switching between processing bottom-up stimuli and engaging top-down OL abilities, which is important for RC (Cartwright et al., 2017; Guajardo & Cartwright, 2016). Behavioral studies using path modeling strategies have provided a nuanced way to disentangle the associations between these variables. In particular, EFs appear to indirectly relate to RC performance by impacting its WR and OL components (Haft et al., 2019; Y.-S. G. Kim, 2020; Spencer et al., 2020).

Brain imaging studies have demonstrated that reading recruits the prefrontal system that underlies EFs. Word-level reading appears to tap the prefrontal cortex, which is thought to subserve the working memory space (i.e., storage and operation) for word stimuli and WR skills (Patael et al., 2018). The dorsal prefrontal cortex has also been implicated in discourse-level processes due to the demands on memory storage, information integration, and attentional shifting (Moss et al., 2011). Recent results have revealed the involvement of the posterior prefrontal regions, such as the precentral gyrus, in not only reading but also math and memory tasks, highlighting the domain-generality of the prefrontal system (Wang et al., 2020).

One particularly important consideration is that at the neurobiological level, regions in the prefrontal cortex have wide and extensive connections with other areas, which forms the core neural substrate of EFs (Friedman & Robbins, 2022; Panikratova et al., 2020; Reineberg et al., 2022). Rather than acting on its own, the prefrontal-executive system is thought to cooperate with other cortical regions and neural systems to support task-relevant demands (Cole et al., 2012, 2013; Zanto & Gazzaley, 2013). Indeed, functional MR imaging studies that use connectivity analyses have revealed the interactions between the prefrontal regions and lateral temporal gyrus during word-level processes (Aboud et al., 2016), and between the prefrontal regions and angular gyrus during RC task performance (H. Kim et al., 2022). Together, these findings shed light on how the prefrontal-executive system is involved in reading.

## The home environment is multifaceted

The multiple neurocognitive systems involved in reading (directly and indirectly) provide different ways through which the home environment could influence children's reading development. (For conceptual illustrations, please see **Figures 1.1-2**.) Various co-occurring factors in the home environment have been linked to children's reading outcomes, including literacy-oriented activities and parental education background. Prior studies have grouped some of these factors together to describe the behavioral processes and structural conditions in the home environment. Consistent with the *Bioecological Model*, these dimensions describe how proximal versus distal variables in the home environment can directly or indirectly influence children's outcomes, respectively (Bronfenbrenner, 1986; Martin & Martin, 2002). In particular, some behaviors are considered proximal variables, including teaching children arithmetic calculations or reading books together aloud, because such processes are directly experienced by the child and beneficial to skill development (Wirth et al., 2022). Structural conditions, such as household financial and parental socioeconomic circumstances, are perceived as indicators of what the child may experience from a distance, or a distal influence/variable (Antonoplis, 2022; Bradley & Corwyn, 2002; Conger & Donnellan, 2007; Duncan & Magnuson, 2012).

The home factors are thought to influence children's cognitive abilities and reading outcomes via experience-driven neural plasticity (Greenough et al., 1987). Landmark studies using large samples have revealed that indices of the home environment predict anatomical brain differences in children. Of note is that these studies have quantified the brain anatomy by gray matter volume, cortical thickness, and surface area, which are known to have functional implications (McDermott et al., 2019; K. G. Noble et al., 2015; Sheridan et al., 2022). Despite these foundational studies, the particular neural systems that mediate the home influences on children's reading development remain elusive. Because the behavioral processes and structural conditions capture different factors and variables in the home environment, the neural mechanisms underlying their linkages with children's reading outcomes could differ, yet to date have not been unpacked.

## The behavioral processes dimension

Behavioral processes in the home environment are thought to be a crucial force in driving children's cognitive development. Some behavioral processes are cognitive enrichment and the provision of learning opportunities (Elardo & Bradley, 1981; Han et al., 2004). The impact of these behavioral processes in the home environment appear to directly impact children's cognitive processes, some combinations of which, in turn, promote academic readiness (Wirth et al., 2022). Further analyses have pinpointed that in the home learning environment, specific literacy-oriented activities can benefit children's reading and language outcomes (Sénéchal, 2006; Wirth et al., 2022).

Literacy-oriented activities at home, collectively known as the home literacy environment (HLE), present opportunities for children to have a direct contact with processes involved in reading. Some of these activities include shared book reading with parents and exposure to written materials (Griffin & Morrison, 1997; Phillips & Lonigan, 2009; Sénéchal, 2006). Children from more enriched HLE backgrounds tend to show greater literacy readiness and better language abilities (Mol et al., 2008; Mol & Bus, 2011a; Zuilkowski et al., 2019).

### *Link with reading development*

As illustrated in Sénéchal's *Home Literacy Model*, the HLE can provide multiple opportunities for children to interact with the written and spoken aspects of language (Sénéchal, 2006; Sénéchal & LeFevre, 2002). Activities in the HLE that have an emphasis on print teach children about letter names, spelling, and pronunciations (Levy et al., 2006; Neumann et al., 2012; Sénéchal, 2006).

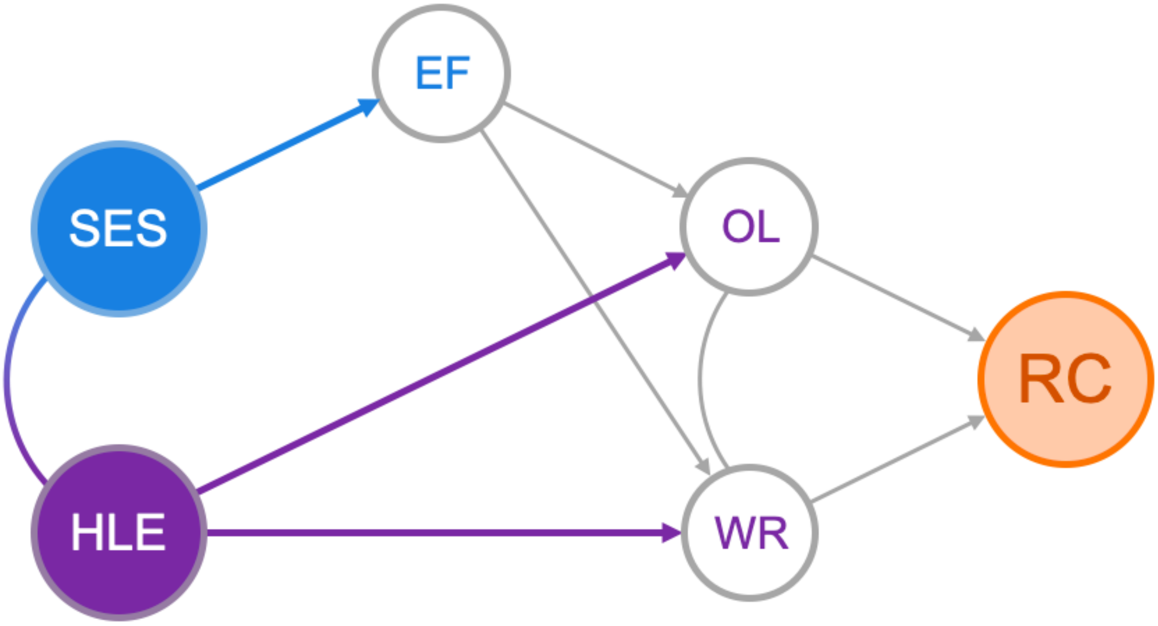
Metrics of the HLE have been shown to predict differences in children's phonological awareness and letter knowledge, both of which are beneficial for developing WR skills and, in turn, RC. Moreover, one brain imaging study has shown that indices of the HLE predict activity in the bilateral occipital-temporal cortices, as well as the left inferior frontal and right superior temporal gyri during a phonological processing task in the scanner (Powers et al., 2016). These regions have been implicated to play a role in children's WR skills (Joseph et al., 2001; Turkeltaub et al., 2002).

### *Link with language abilities*

According to Sénéchal's *Home Literacy Model*, the HLE also includes activities that place a focus on meaning and facilitate children's OL development (Sénéchal, 2006; Sénéchal & LeFevre, 2002). Studies have revealed that book reading activities with parents are an excellent way to introduce children to diverse vocabulary words, as well as to scaffold language learning and comprehension (Mol et al., 2008; C. Noble et al., 2019; Zucker et al., 2013). During these activities, children may spend time listening and piecing ideas together in stories that are orally rendered by parents. Observational studies have revealed that, compared to non-reading periods, reading times include higher adult word counts and more parent-child conversational turns, suggesting that parent-child language interaction is elevated in both quantity and quality in the HLE (Gilkerson, Richards, & Topping, 2017; Gilkerson, Richards, Warren, et al., 2017). It has been shown that through these meaning-focused variables, the HLE predicts differences in children's vocabulary knowledge and listening comprehension abilities. Moreover, brain imaging studies using story listening tasks have shown that indices of the HLE predict activity in the left lateral temporal cortex (e.g., temporal pole and inferior-middle temporal regions), which are areas implicated in lexico-semantic and syntactic processes (Ferstl et al., 2008; Friederici, 2011). The HLE has also been linked to activity in the left angular gyrus and posterior cingulate cortex that support discourse-level processes (Ferstl et al., 2008; Mar, 2011).

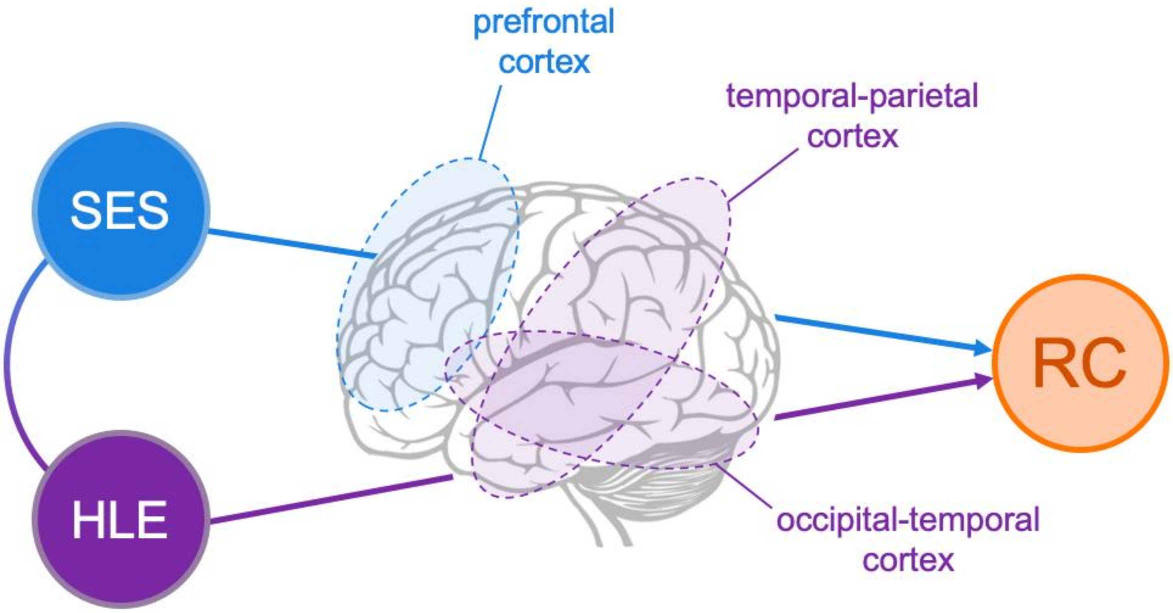
Put together, the HLE appears to be a powerful contributor to children's reading development, particularly by its influence on the neural correlates of WR and OL abilities known to impact RC outcomes. Importantly, across these behavioral and brain imaging studies, analyses controlled for parental socioeconomic backgrounds, thus highlighting a link between the HLE and children's language and reading that is unique from broader SES impacts on these brain systems.

**Figure 1.1**. Conceptual model for the relations between the HLE, parental SES, and cognitive correlates of reading.



*Note*. SES = socioeconomic status, HLE = home literacy environment, EF = executive function, OL = oral language, WR = word recognition, and RC = reading comprehension.

**Figure 1.2**. Conceptual model for the relations between the HLE, parental SES, and neural correlates of reading.



### The structural conditions dimension

Structural conditions of the home environment can be represented by parental or household socioeconomic circumstances, which describe “possession of normally valued social and economic resources” (Antonoplis, 2022).  Some of these indicators typically include parental level of educational attainment and occupational employment, as well as the level of household income or incomes-to-needs ratio, thus making them more distal factors in a child’s environment (Antonoplis, 2022; Cirino et al., 2002). A common thread among these distal variables is that they span various sociocultural opportunities, material resources, and other structural means. However, of note, each index could embody unique aspects of the child’s environment and development (Conger & Donnellan, 2007; Duncan & Magnuson, 2012, 2003).

Parental level of educational attainment, a component of socioeconomic status (SES), has been commonly used as an indicator of the home structural conditions (Antonoplis, 2022; Mueller & Parcel, 1981). Reports have posited that parental education is linked to the quality of parent-child interactions, which could impact the degree of cognitive enrichment, psychoemotional support, and/or scaffolding practices that the child experiences (Duncan & Magnuson, 2012, 2003). Because of its broad influence, parental SES has been shown to predict differences in multiple neurocognitive systems in children, including language and executive functions, and not just their reading outcomes (McDermott et al., 2019; K. G. Noble et al., 2005, 2015; Romeo et al., 2022).

#### *Link with reading development*

Numerous studies have linked parental SES to children’s reading outcomes (Aikens & Barbarin, 2008; Bowey, 1995; Kieffer, 2012). Meta-analyses have shown that parental SES explains substantial variance in children’s academic attainment (Sirin, 2005; White, 1982). Children from more affluent or higher SES backgrounds tend to score higher on measures of literacy readiness at school entry, as well as later WR outcomes and RC attainment than those from lower social class backgrounds (Bowey, 1995; Hecht et al., 2000; van der Kleij et al., 2023). Some reports suggest that parental SES relates to proximal variables, such as parent-child interaction and school support, that could have a downstream impact on children’s academic outcomes, including reading (Devine et al., 2016; Kieffer, 2012). Encouragingly, analyses have been able to pinpoint the impact of distal

SES variables on children's development through at least two neurocognitive systems: OL and EF (Merz et al., 2019; K. G. Noble et al., 2005).

Parental SES has been linked to the quality of parent-child language interactions, which could be a vehicle for the influence on children's reading development. In studies that use naturalistic strategies to capture day-to-day spoken language variables, parental education has been revealed to elevate the linguistic quality in the home environment (Hoff, 2003; Magnuson et al., 2009; Rowe, 2008). Some of the spoken language variables that are captured during parent-child language interactions include word tokens, overheard speech, and taking turns in conversation (Gilkerson, Richards, Warren, et al., 2017). While parental education has been related to the linguistic quality in the home environment, findings have revealed that "structural constraints" like financial scarcity and hardship can affect how parents speak to their children (Ellwood-Lowe et al., 2022). The links between different components of SES (parental education and household finances) and the home language environment illustrate the prevalent impact of the home structural conditions on language development. However, these studies have yet to account for the HLE, which specifically focuses on parent-child language interactions related to literacy. Such studies are needed to unpack the links between parental SES and children's language and reading abilities, as some behavioral findings have revealed that the HLE, but not parental SES, is uniquely related to children's WR and RC outcomes through their OL abilities (Hamilton et al., 2016; Inoue et al., 2018a).

### *Link with executive abilities*

The way that parental SES relates to children's prefrontal-executive system could provide a mechanism for how SES impacts reading outcomes. There is a well-established link between parental SES and various metrics of children's prefrontal-executive system, using behavioral assessments of EFs (Hackman et al., 2015; Lawson & Farah, 2017; Sarsour et al., 2011), brain functional activity during tasks that tax EFs (Finn et al., 2017; Kishiyama et al., 2009; Sheridan et al., 2012), and anatomical measurement of the prefrontal cortex (Lawson et al., 2013; Shaked et al., 2018). Further, the influence of distal SES variables on EFs appear to yield downstream effects on children's school readiness and academic outcomes, and does not simply show immediate impacts (Z. T. Barnes et al., 2022; Blair & Razza, 2007; Hemmerechts et al., 2017). Some of these findings in particular demonstrate the impact of parental education indirectly through children's

EFs on their reading outcomes, even after carefully controlling for background vocabulary knowledge (Waters et al., 2021). Parental education has been shown to predict activity differences in children's prefrontal cortex during an in-scanner phonological processing task, and that these associations overlapped with OL indices (vocabulary knowledge) and perceptual abilities (Conant et al., 2017). These results are in line with those suggesting that parental SES and indices of children's prefrontal-executive system share substantial overlapping variance with OL measures (K. G. Noble et al., 2005; Romeo et al., 2022; Weiland et al., 2014).

## A model of the home environment and reading development

Based on the aforementioned influences of the HLE and parental SES, a unified model is needed to systematically examine how these variables in the home environment impact children's reading development. RC involves WR skills, OL abilities, and EFs, as well as their underlying neural correlates, that could serve as candidate pathways through which the HLE and parental SES influence reading development. Previous findings have shown unique patterns of associations between the HLE and parental SES with the neurocognitive correlates of children's reading outcomes. However, studies analyzing the relation between the HLE and children's reading outcomes have yet to account for EFs. Reports examining links between parental SES and children's EFs and reading outcomes have yet to consider the contribution of the HLE. To this end, the primary hypotheses are:

- ***Hypothesis 1***. Controlling for parental SES, the HLE impacts children's RC outcomes by influencing the WR skills and the underlying brain occipital-temporal regions supporting WR skills.
- ***Hypothesis 2***. Controlling for parental SES, the HLE will relate to children's RC outcomes by affecting the OL abilities and underlying brain temporal-parietal regions supporting OL abilities.
- ***Hypothesis 3***. After accounting for the HLE, parental SES will relate to children's prefrontal-EF systems, which will then have downstream associations with WR skills, OL abilities, and, ultimately, RC.

## Specific studies in the current thesis

With this unified model of the home environment and reading development, three interrelated studies were conducted to examine the relations between the HLE, parental SES, and neurocognitive correlates of children's reading outcomes. Analyses were conducted in a longitudinal sample of children who underwent anatomical brain imaging and were assessed for reading skills and cognitive abilities after first grade, and then returned for evaluation of RC outcomes after second grade.

- ***Study 1*** examines the relations between the HLE, parental SES, and WR skills, OL abilities, and EFs in children's RC outcomes.
- ***Study 2*** maps the relative impacts of the HLE and parental SES on neural systems that are linked to children's WR skills, OL abilities, and EFs.
- ***Study 3*** investigates the extent to which neural systems impacted by the HLE and parental SES predict children's RC outcomes.

# CHAPTER 2

## Study 1: The home environment and cognitive correlates of reading

### Motivation

The aim for **Study 1** was to understand how the HLE and parental SES influence children's RC development through its cognitive correlates. As discussed in the introduction, RC, the endpoint in children's reading development, is directly related to WR skills and OL abilities (Hoover & Gough, 1990; Quinn & Wagner, 2018). It is well-established that difficulties with WR skills and/or weaknesses in OL abilities result in challenges in RC performance (Peng et al., 2019; Spencer & Wagner, 2018). More recently, using path modeling strategies, studies have shown that EFs also relate to children's RC outcomes indirectly through the component WR skills and OL abilities (Haft et al., 2019; Y.-S. G. Kim, 2020; Spencer et al., 2020). Here, the current study builds upon these findings and use path modeling strategies to tease apart the extent to which the HLE and parental SES relate to children's RC outcomes through WR skills, OL abilities, and EFs.

The HLE and parental SES capture different factors and variables in the home environment, thus their associations with children's RC outcomes are likely explained by different mechanisms. The HLE includes literacy-oriented activities and reading behaviors, which are some proximal variables that could provide children an exposure to reading processes (Sénéchal, 2006; Sénéchal & LeFevre, 2002). On the other hand, parental SES, such as the level of educational attainment, represents distal factors and structural resources that permeate proximal variables and other factors, which in turn impact children's reading development (Aikens & Barbarin, 2008; Bowey, 1995; Kieffer, 2012).

### Links between the home environment and cognitive correlates of reading

#### The home environment and children's WR skills

The HLE has been associated with children's reading development. Children from an enriched HLE tend to score higher on measures of reading skills and attainment, as compared to peers with limited reading experiences (Bracken & Fischel, 2008; Mol & Bus, 2011b). According to

Sénéchal's *Home Literacy Model*, a beneficial HLE includes print-focused activities, which then can bolster children's familiarity with written words, awareness of the spelling patterns, and exposure to speech-sounds and word-forms correspondences (Sénéchal, 2006; Sénéchal & LeFevre, 2002). It has been shown that the HLE relates to children's letter knowledge and phonological awareness at kindergarten, which later support their WR skills by the end of first and second grades (Bracken & Fischel, 2008; Griffin & Morrison, 1997; Levy et al., 2006). Children's WR skills mediate the influence of the HLE on later RC outcomes (Hamilton et al., 2016; Inoue et al., 2018a). Of note, the aforementioned studies carefully controlled for parental SES, thus emphasizing the unique contribution of the HLE in children's reading development.

### The HLE and children's OL abilities

The HLE has been shown to benefit children's language development and, in turn, reading outcomes. Sénéchal's *Home Literacy Model* suggests that the HLE includes meaning-focused activities, like shared book reading with parents, that can promote children's OL abilities (Sénéchal, 2006; Sénéchal & LeFevre, 2002). Books contain more sophisticated and complex language, as well as diverse vocabulary items as compared to daily conversations or interactions between parents and children (Gilkerson, Richards, & Topping, 2017). Vocabulary items and complex sentence structures in these books are also often embedded in supporting context and story structure that may further promote language learning (Wasik et al., 2016). At the same time, shared reading presents opportunities for parents to facilitate children's comprehension abilities by bolstering their background knowledge and using scaffolding strategies, such as making inferences to expand on the book's content (Blewitt et al., 2009; Mol et al., 2008; Reese & Cox, 1999). Indeed, the HLE has been correlated with indices of children's OL abilities, including vocabulary knowledge and listening comprehension. It has been further shown that uniquely from parental SES, the HLE relates to children's RC outcomes through OL abilities (Hamilton et al., 2016; Inoue et al., 2018b).

### Parental SES and children's EFs

Parental SES has been linked to children's academic outcomes, as well as EFs. Children with higher parental SES backgrounds tend to score higher on measures that assess academic skills, including reading and math, as well as EFs (Ardila et al., 2005; Conway et al., 2018; Sarsour et al., 2011; St. John et al., 2019). Meta-analytic and large-scale approaches have shown that SES-related differences in EFs are evident across the socioeconomic spectrum when assessed continuously, and not just limited to those in poverty or adverse circumstances (Hackman et al., 2015; Last et al., 2018; Lawson et al., 2018). EFs play an important role in children's school readiness and academic attainment (Cortés Pascual et al., 2019; Gathercole et al., 2004; Spiegel et al., 2021). As such, findings have revealed that EFs mediate the influence of parental SES on children's academic outcomes (Waters et al., 2021). However, studies have yet to examine the relations between parental SES and children's EFs and reading outcomes while also accounting for the HLE.

## Current study

Using path modeling strategies, the current study aims to elucidate the extent to which the HLE and parental SES relate to children's RC outcomes through WR skills, OL abilities, and EFs. Accounting for these variables in the same model could provide valuable insights into how the home environment influences reading development. To this end, the following three hypotheses are posited:

- ***Hypothesis 1***. Controlling for parental SES, the HLE will relate to children's WR skills, which in turn will predict RC outcomes.
- ***Hypothesis 2***. Uniquely from parental SES, the HLE will predict children's OL abilities, which in turn will predict RC outcomes.
- ***Hypothesis 3***. After accounting for the HLE, parental SES will predict children's EFs, which in turn will predict OL abilities and WR skills, and, ultimately, RC outcomes. In other words, SES will directly predict EFs, with the impact of EFs on RC mediated by WR and OL.

## Methods

Data and related procedures for the current study were carried out in accordance with the Institutional Review Board regulations at Vanderbilt University.

### Sample and Children’s Demographic Information

Participants were recruited from local schools, clinics, and pediatricians’ offices, as well as the greater Middle Tennessee region. All participating children were native English speakers, with normal or correctable visual or auditory differences, and did not demonstrate any history or presence of a pervasive developmental disorder or known neurobiological disorder. For the current sample, children with ADHD were not excluded, provided that they could sustain attention for assessments. Upon enrollment, children provided informed consent, and their parents completed consent.

Data were drawn from 198 children after their successful completion of first grade (*m* age = 7.47, *sd* = 0.36, *range* = 6.42 - 8.33). The sample included 105 (53%) girls and 93 (47%) boys. Five children (3%) were Asian, 23 (12%) Black, 150 (76%) White, 16 (8%) more than one race, and 4 (2%) either did not or preferred not to report. Ten children (5%) identified as Hispanic/Latino.

Of the original sample, 167 children returned for a follow-up visit after completing second grade. Analyses in the current study used data collected from these 167 children. This subsample included 93 (56%) girls and 74 (44%) boys. Five children (3%) were Asian, 19 (11%) Black, 125 (75%) White, 14 (8%) more than one race, and 4 (2%) either did not or preferred not to report. Ten children (6%) identified as Hispanic/Latino.

Information about the school that children attended was collected by identifying whether or not their school received Title 1 Federal Supplement funds—that is, whether more than 40% of students were receiving free or reduced-price lunch and/or living below the poverty line based on publicly available data (c.f., del Tufo et al., 2019).

Children’s perceptual reasoning, an index for fluid intelligence, was measured using the *Matrix Reasoning* subtest from the *Weschler Abbreviated Scale for Intelligence* (WASI; Wechsler, 2011).

### Parents’ Backgrounds & Questionnaires

Familial history of reading difficulties was queried by asking parents to complete the *Adult Reading History Questionnaire* (ARHQ; Lefly & Pennington, 2000). The *ARHQ* contains 23 five-point items (with partial credit of 0.5-point increment), which ask about the respondent's difficulties with learning to read in elementary school, experiences with reading in secondary and upper education, attitude toward reading, and current literacy practices (Nguyen et al., 2022; Welcome & Meza, 2019).

To capture parental SES, parents were asked to report their highest level of educational attainment. The reported level of education was then rated on a seven-point scale, where 1 = "*less than seventh grade*", 2 = "*junior high school (ninth grade)*", 3 = "*partial high school (tenth or eleventh grade)*", 4 = "*high school graduate (whether private preparatory, parochial, trade, or public school)*", 5 = "*partial college (at least one year) or specialized training*", 6 = "*standard college or university graduation*", or 7 = "*graduate or professional training (graduate degree)*".

Data about the HLE were collected from parents' responses on questions about reading behaviors at home. Parents were asked two questions using a six-point scale response format (1 = *not at all,* 2 = *once or twice,* 3 = *three or four times,* 4 = *five to six times,* 5 = *daily,* and 6 = *more than once a day*). The first question asked, "The next question is about your child from pre-school through kindergarten (before he/she entered first grade): In a typical week, how often did an adult in the household (you, your spouse) and your child read books together?" (*m* = 3.34, *sd* = 1.12, *range* = 0 - 5). The other question asked, "In a typical week, how often does your child read voluntarily?" (*m* = 2.94, *sd* = 1.47, *range* = 0 - 5). Composite scores were calculated based on the responses from these questions and were used to capture the HLE.

## Child Reading & Cognitive Assessments

Performance data for children's WR skills, OL abilities, and EFs were collected after first grade, and RC performance was evaluated after second grade.

### *WR skills*

The Letter-Word Identification and Word Attack subtests from the *Woodcock-Johnson* (Mather & Jaffe, 2016), as well as Phonemic Decoding Efficiency and Sight Word Efficiency subtests from the *Test of Word Reading Efficiency* (TOWRE; Torgesen et al., 1999) were administered. These subtests were used to assess children's ability to recognize real words and decode non-words under untimed conditions to capture accuracy (in the *WJ* subtests), versus timed conditions to capture fluency (in the *TOWRE* subtests). The reliability coefficients for the *WJ* subtests fall between 0.91-0.94, whereas the coefficients for the *TOWRE* subtests are between 0.96-0.97. Standard scores on the *WJ* and *TOWRE* subtests were used.

### ***OL abilities***

The Receptive Vocabulary subtest from the *Test of Word Knowledge* (TOWK; Wiig & Secord, 1992) was administered, which asks children to identify one out of a set of pictures that best represent an orally presented word. The Vocabulary subtest from the WASI was also administered, which evaluates children's ability to name visually presented items (the first few) and to define words presented visually and orally. *T*-scores on the *WASI* Vocabulary subtest were used. In addition to standardized tests, children were asked to listen to two in-house experimental passages, one narrative and the other expository, and oral comprehension was evaluated by multiple-choice questions (orally administered) that required children to identify factual information, make interpretations, and apply strategies or critical analyses (for further information about these passages, please refer to del Tufo et al., 2019). Raw scores on these passages were based on the total number of questions that children answered correctly. The reliability coefficients for the *WASI* and *TOWK* subtests are reported as 0.91 and 0.89. Scaled scores on the *TOWK* Receptive Vocabulary subtest, *T*-scores on the *WASI* Vocabulary subtest, and raw scores on the passages were used in analyses. Age was included in the formal analyses (see below), which accounts for the scores on the passages being raw scores.

### ***EFs***

To capture cognitive flexibility, the Animal Sorting subtest from the *Neuropsychological Assessment* (NEPSY; Korkman et al., 2007) was administered by presenting children with eight cards for them to sort into two groups of four, in as many categorically plausible ways as possible. To measure working memory, the Listening Recall subtest from the *Working Memory Test Battery* (WMTB for children; Pickering & Gathercole, 2001) was administered, which requires children to listen to a sentence, decide whether it is true or not, and then recall its last word. The assessment was administered in six trials, with each span length ranging from one to six words. The reliability coefficients for the *NEPSY* fall between 0.70-0.90, and the coefficient for the *WMTB* subtest is reported as 0.83. Scaled scores from the *WMTB* Listening Recall and *NEPSY* Animal Sorting subtests were used.

### *RC performance*

The Passage Comprehension subtest from the *WJ* (Mather & Jaffe, 2016) was administered, which evaluates children's ability to read passages and at the end of each, fill in a missing word (modified cloze format). The Comprehension subtest from the *Gates-MacGinitie Reading Test* (GMRT; MacGinite et al., 2002) was also administered, which requires children to read passages and, following each passage that remains in view, answer written multiple-choice questions. The reliability coefficients for the *WJ* and *GMRT* subtests are reported as 0.88 and 0.93. Standard scores on the *WJ* Passage Comprehension subtest and *Extended Scale Scores* (ESS) on the *GMRT* Comprehension subtest were used.

## Analyses

### *Preliminary analyses*

Preliminary analyses were conducted to report descriptive statistics on the collected measures and surveys, as well as calculate pairwise correlations among them. Missing data were addressed and imputed using the *impute()* function available in R. To calculate composite scores for children's performance on WR, OL, EF, and RC measures, scores on individual subtests for each construct were first transformed into *z*-scores, using the *scale()* function, and then averaged. The background variables controlled for in analyses included parental reading history and child demographic details, including age, biological sex, perceptual IQ, and school information (Title 1 Status); the variables of interest included parental SES (level of educational attainment) and the HLE indices, as well as composite scores for children's performance on WR, OL, EF, and RC measures.

### *Path analyses*

Path analyses were conducted using the *sem()* function in the *lavaan* package (Rosseel, 2012) to analyze the relations between the home environment indices (parental SES and the HLE) and children's cognitive and reading abilities.

An initial path model was constructed by accounting for all possible associations among these variables of interest. Confounding variables were included in the model as covariates (parental reading history, and, children's age, biological sex, perceptual IQ, and school information). The follow threes steps were taken while building the path model:

**Step 1**.

RC performance was predicted by OL and WR variables. The OL and WR variables were modeled as covaried in order to reflect the *Simple View of Reading* model (Quinn & Wagner, 2018; Tunmer & Chapman, 2012).

**Step 2**.

EF variables were then incorporated into the model to predict WR and OL measures, as done in previous studies (Y.-S. G. Kim, 2020; Spencer et al., 2020).

**Step 3**.

Parental SES and the HLE were added to the model and were specified to regress against children's performance on WR, OL, EF, and RC.

Any non-significant paths were one-by-one constrained to zero to yield the final model. Then, using the standard errors, the levels of significance were inferred via a bootstrapping approach (Fritz et al., 2012; Rosseel, 2012). For each model, satisfactory fit was determined by non-significant $\chi^2$ (chi-square), *CFI* and *TLI* (Comparative Fit and Tucker-Lewis Indices) greater than or equal to 0.95, and *RSMEA* (Root Mean Square Error of Approximation) and *SRMR* (Standardized Root Mean Square Residual) values less than 0.05 (Hu & Bentler, 1999). Model comparison was performed using the *anova()* function.

## Results

Descriptive statistics of the current sample can be found in **Table 2.1**, which includes information on background variables collected [at baseline] from parents (reading history) and children (age, biological sex, school information [Title 1 Status], and perceptual reasoning), as well as home environment indicators (the HLE and parental SES), and measures of children's WR skills, OL abilities, EFs, and RC outcomes.

**Table 2.1**. Descriptive statistics for the current sample (*N* = 167).

| | | ***M*** | ***SD*** | ***Min*** | ***Max*** |
|---|---|---|---|---|---|
| **Parent surveys** | | | | | |
| 1 | Reading History | 27.93 | 16.63 | 2 | 74 |
| 2 | SES, parental education | 6.13 | 0.91 | 3 | 7 |
| 3 | HLE | 3.13 | 1.09 | 0 | 5 |
| a | RQ 1, shared reading | 3.35 | 1.11 | 0 | 5 |
| b | RQ 2, print exposure | 2.92 | 1.50 | 0 | 5 |
| **Child variables** | | | | | |
| ***Demographic information*** | | | | | |
| 4 | Age (after 1st grade) | 7.46 | 0.35 | 6.42 | 9.33 |
| 5 | Biological Sex | 93 (56%) girls | | | |
| 6 | Perceptual IQ | 53.00 | 8.67 | 29 | 80 |
| 7 | School (Title 1 Status) | 20 (12%) attended | | | |
| ***WR skills*** | | | | | |
| 8 | WJ Basic Reading | 107.89 | 13.04 | 70 | 136 |
| 9 | TOWRE Total Reading Efficiency | 104.98 | 15.21 | 66 | 131 |
| ***OL abilities*** | | | | | |
| 10 | TOWK Receptive Vocabulary | 12.58 | 2.87 | 3 | 17 |
| 11 | WASI Vocabulary | 53.38 | 10.88 | 27 | 80 |
| 12 | Narrative Text Listening Comp. | 4.19 | 1.64 | 0 | 8 |
| 13 | Expository Text Listening Comp. | 6.50 | 1.29 | 2 | 8 |
| ***EFs*** | | | | | |
| 14 | NEPSY Animal Sorting | 9.08 | 3.54 | 1 | 18 |
| 15 | WMTB Listening Recall | 98.97 | 19.07 | 11 | 139 |
| ***RC outcomes*** | | | | | |
| 16 | WJ Passage Comprehension | 106.72 | 12.61 | 73 | 133 |
| 17 | GMRT Comprehension | 435.10 | 40.25 | 308 | 518 |

### *Preliminary findings*

Pairwise correlations among background variables, as well as composite scores from measures of interest were calculated (see **Table 2.2**). Composite scores were then submitted to formal path modeling analyses.

**Table 2.2**. Pairwise correlations among the collected measures and surveys (*N* = 167).

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Parent surveys** | | | | | | | | | | | | |
| 1 | Reading history | - | | | | | | | | | | |
| 2 | SES, parental education | **-0.209** | - | | | | | | | | | |
| 3 | HLE | **-0.308** | **0.221** | - | | | | | | | | |
| **Child variables** | | | | | | | | | | | | |
| ***Demographic information*** | | | | | | | | | | | | |
| 4 | Age | 0.053 | -0.048 | -0.067 | - | | | | | | | |
| 5 | Biological sex | -0.079 | 0.060 | **-0.079** | 0.061 | - | | | | | | |
| 6 | Perceptual IQ | -0.017 | **0.181** | 0.104 | 0.065 | **-0.157** | - | | | | | |
| 7 | School (Title 1 Status) | 0.115 | **-0.275** | **-0.112** | -0.034 | 0.037 | -0.149 | - | | | | |
| ***Behavioral measures*** | | | | | | | | | | | | |
| 8 | WR skills | **-0.216** | **0.366** | **0.325** | -0.102 | 0.008 | **0.234** | **-0.228** | - | | | |
| 9 | OL abilities | **-0.193** | **0.372** | **0.365** | 0.131 | 0.009 | **0.313** | **-0.280** | **0.447** | - | | |
| 10 | EFs | -0.132 | **0.268** | **0.219** | 0.046 | **-0.148** | **0.359** | **-0.176** | **0.426** | **0.491** | - | |
| 11 | RC outcomes | **-0.226** | **0.356** | **0.415** | -0.046 | 0.060 | **0.280** | **-0.239** | **0.705** | **0.630** | **0.428** | - |

*Note*. Coefficients in **bold** met $p < 0.05$.

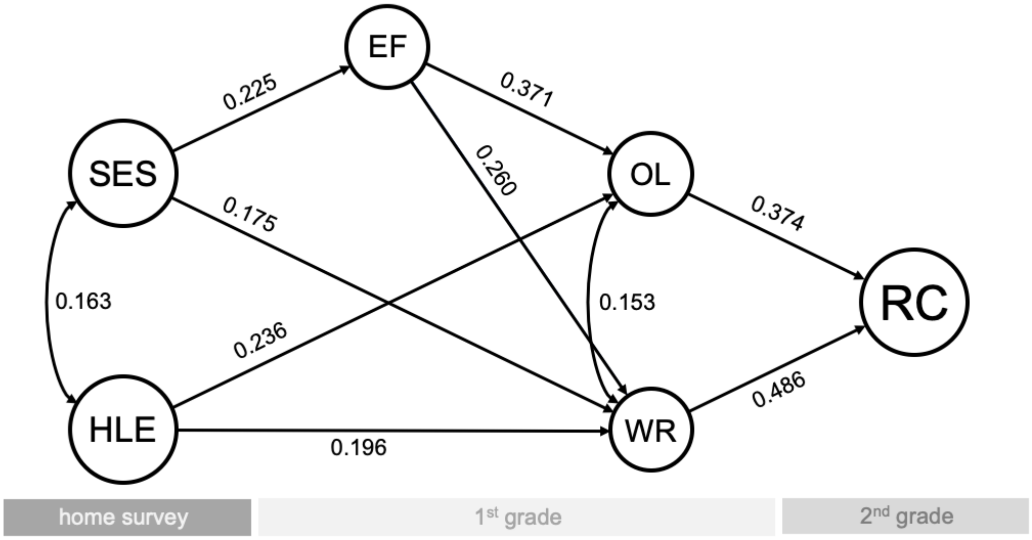
Correlations between variables revealed that the HLE and parental SES were positively correlated ($r = 0.221$, $p < 0.05$). The HLE was positively correlated with WR skills ($r = 0.325$), OL abilities ($r = 0.365$), and EFs ($r = 0.219$) measured after first grade, as well as with RC outcomes ($r = 0.415$) assessed after second grade (all $p$'s < 0.05). Parental SES was positively correlated with WR skills ($r = 0.366$), OL abilities ($r = 0.372$), and EFs ($r = 0.268$) measured after first grade, as well as with RC outcomes ($r = 0.356$) assessed after second grade (all $p$'s < 0.05).

### *Path modeling results*

The initial model that included all possible associations among the home indices (the HLE and parental SES) and children's cognitive and reading abilities provided decent fit to the data, $\chi^2 = 0.042$ ($df = 1$, $p = 0.838$), $CFI = 1.000$, $TLI = 1.093$, $RMSEA = 0.000$, and $SRMR = 0.001$.

The final model, for which non-significant paths were constrained to zero, can be found in **Figure 2.1**. This more parsimonious model also provided a decent fit to the data, $\chi^2 = 8.558$ ($df = 8$, $p = 0.128$), $CFI = 0.991$, $TLI = 0.961$, $RMSEA = 0.039$, and $SRMR = 0.024$. When compared to the model that included all possible associations among variables to the more parsimonious model (constraining non-significant paths to zero), findings revealed that the more parsimonious model marginally significantly showed a superior model fit (*delta* $\chi^2 = 8.516$, $p = 0.074$). Because of this finding, as well as in the interest of parsimony, the constrained model was used as the final model.

**Figure 2.1**. Final path model.



*Note.* All paths shown met $p < 0.05$.

**Table 2.3**. Direct and indirect effects for the HLE predictions.

| **Path** | ***b*** | ***se*** | ***p*** |
|---|---|---|---|
| ***Direct effects of HLE*** | | | |
| HLE → WR | 0.196 | 0.073 | 0.003 |
| HLE → OL | 0.236 | 0.051 | 0.000 |
| ***Indirect effects of HLE*** | | | |
| HLE → WR → RC | 0.095 | 0.034 | 0.005 |
| HLE → OL → RC | 0.088 | 0.026 | 0.001 |

*Note*. All coefficients met $p < 0.05$.

***Effects of the HLE on children's reading outcomes and OL abilities*** **(Table 2.3)**

The HLE was shown to have direct and positive effects on children's WR skills ($b = 0.196$) and OL processes ($b = 0.236$) measured after first grade (both $p$'s $< 0.05$).

The HLE was found to have an indirect and positive effect through children's WR skills measured after first grade on their RC outcomes assessed after second grade ($b = 0.095$, $p < 0.05$). The HLE also had an indirect and positive effect through children's OL processes measured after first grade on RC outcomes assessed after second grade ($b = 0.088$, $p < 0.05$), thus suggesting that the HLE influences children's RC outcomes through both WR skills and OL abilities.

**Table 2.4**. Direct and indirect effects for parental SES predictions.

| **Path** | ***b*** | ***se*** | ***p*** |
|---|---|---|---|
| ***Direct effects of SES*** | | | |
| SES → WR | 0.175 | 0.075 | 0.008 |
| SES → EF | 0.225 | 0.062 | 0.001 |
| ***Indirect effects of SES*** | | | |
| SES → WR → RC | 0.085 | 0.034 | 0.011 |
| SES → EF → WR → RC | 0.029 | 0.012 | 0.014 |
| SES → EF → OL → RC | 0.031 | 0.012 | 0.007 |

*Note*. All coefficients met $p < 0.05$.

### *Effects of parental SES on children's reading outcomes and EFs* **(Table 2.4)**

SES was shown to have direct and positive effects on children's WR skills ($b = 0.175$) and EF abilities ($b = 0.225$) measured after first grade (both $p$'s $< 0.05$).

SES was also found to have an indirect and positive effect through children's WR skills measured after first grade on their RC outcomes assessed after second grade ($b = 0.085$, $p < 0.05$). Moreover, the indirect effects of SES through children's EF abilities on RC outcomes were mediated by WR skills ($b = 0.029$) and OL processes ($b = 0.031$) (both $p$'s $< 0.05$), thus suggesting that the influences from parental SES on children's RC outcomes originates in part through its impact on EFs.

## Discussion

Our aim for **Study 1** was to examine the extent to which the HLE and parental SES relate to children's RC outcomes through WR skills, OL abilities, and EFs. Findings showed that controlling for parental SES, the HLE positively related to children's WR skills and OL abilities and, in turn, RC outcomes. Uniquely from the HLE, parental SES was positively associated with children's EFs and ultimately impacted RC outcomes through WR skills and OL abilities. Additionally, and contrary to the initial hypotheses, a direct and positive relation of parental SES on children's WR skills was observed.

### The home environment and children's WR skills

Controlling for parental SES, the HLE was related to children's WR skills and, in turn, RC outcomes. This result is supported by a wealth of evidence on the contribution of the HLE in preparing children to learn how to read, as well as in predicting future reading attainment (Mol & Bus, 2011b). According to Sénéchal's *Home Literacy Model,* behaviors in the home environment that place an emphasis on print and expose children to letter names, spelling, and pronunciations lay the foundation for acquisition of WR skills (Sénéchal, 2006). Some have shown that the HLE relates to children's phonological awareness and letter knowledge that, in turn, support WR skills (Hamilton et al., 2016; Inoue et al., 2018a).

Even after controlling for the overlapping variance with the HLE, parental SES remained directly related to children's WR skills. This finding is consistent with previous path modeling studies that have revealed that the HLE and parental SES have common associations with children's phonological awareness and letter knowledge, which in turn predict WR skills, reading fluency, and RC outcomes (Hamilton et al., 2016; Inoue et al., 2018a). Notably, these prior findings did not include EFs as a possible mediator to explain the relation between parental SES and children's WR skills. In the current study, the impact of parental SES on children's WR skills was hypothesized to be indirect through EFs (see discussion below). Contrary to the initial hypotheses, parental SES remained related to children's WR skills even after taking into account the HLE and children's EFs. Parental SES could relate to children's WR skills in ways that are unique from the contributions of the metrics for the HLE and children's EFs. For example, prior studies have suggested that parental SES is indirectly associated with children's academic outcomes through parents' academic expectations and emphasis on education (Davis-Kean, 2005; Tan et al., 2020;

Yeung et al., 2022). Some studies have suggested that uniquely from reading behaviors in the HLE, parents' literacy interests and expectations could explain the impact of parental SES on children's reading outcomes (Georgiou et al., 2021; Martini & Sénéchal, 2012; Pezoa et al., 2019). These results suggest that other variables or cognitive factors may be in the mix to explain the link between parental SES and children's reading development.

### The HLE and children's OL abilities

Uniquely from parental SES, the HLE was associated with children's OL abilities and, in turn, RC outcomes. This finding is consistent with previous studies that track the unique relation between the HLE and children's vocabulary knowledge (Hamilton et al., 2016; Inoue et al., 2018a). The current study used a composite score of both vocabulary knowledge and listening comprehension to capture children's OL abilities. According to Sénéchal's *Home Literacy Model,* book reading activities can foster children's language development by providing a rich source of linguistic experiences (Sénéchal, 2006). Books, for instance, include vocabulary items that are not always available in everyday conversations, and therefore could widen children's lexico-semantic networks (Gilkerson, Richards, & Topping, 2017; Wasik et al., 2016). Parents could also leverage shared reading opportunities to scaffold children's language processes, do story-walks, and engage in activities supporting comprehension (Blewitt et al., 2009; Mol et al., 2008; Reese & Cox, 1999). Moreover, because OL abilities are known to become increasingly crucial in RC performance as students advance to secondary education and beyond, they could mediate a long-lasting impact of the HLE (Mol & Bus, 2011b).

While preliminary analyses showed a bivariate correlation between parental SES and children's OL abilities, this association was substantially attenuated after including the HLE in the model. This finding aligns with previous path modeling studies that account for parental SES and the HLE variables in parallel to demarcate their impacts on measures of children's OL abilities (Hamilton et al., 2016; Inoue et al., 2018a). These studies showed that when the HLE is taken into account, parental SES did not have a unique effect on children's vocabulary knowledge. These findings suggest that the overlapping variance with the HLE provides an explanation for the link between parental SES and children's OL differences. These results thus support the unique and specific association between the HLE and language development regardless of parental SES backgrounds, as well as suggest that interventions targeting reading behaviors and upstream language abilities could influence children’s reading outcomes (Dowdall et al., 2020; Lonigan & Whitehurst, 1998; Troseth et al., 2020).

### Parental SES and children’s EFs

Although the HLE was shown to be correlated with children’s EFs in bivariate analyses, path findings suggested that their association diminished and were non-significant after accounting for parental SES. One study has shown that controlling for parental SES, indices of the home learning environment relate to children’s academic outcomes directly, rather than indirectly through their EFs (Devine et al., 2016). The current findings also revealed that controlling for parental SES, the HLE relates to children’s reading outcomes directly, but not indirectly through EFs. It is possible that the overlapping variance with parental SES may explain prior reports of a link between the HLE and children’s EF differences (Korucu et al., 2020).

Results suggested that uniquely from the HLE, parental SES was directly associated with children’s EFs and in turn—via WR skills and OL abilities on—RC outcomes. Extant evidence clearly supports the finding that parental SES is associated with children’s EFs (Hackman et al., 2015; Last et al., 2018; Lawson et al., 2018). Children from higher SES backgrounds and with stronger EFs tend to score higher on reading measures (Z. T. Barnes et al., 2022). These findings are consistent with past literature showing the associations between parental SES and differences in children’s EFs and school readiness (Blair & Razza, 2007). What is noteworthy here is that the present findings showed the unique relations between parental SES, children’s EFs, and reading outcomes after controlling for the contributions of the HLE and children’s OL abilities. In other words, the current findings suggest that EFs serve as a cognitive mechanism through which distal SES factors impact children’s reading development.

## Additional considerations and future directions

Some limitations of the current study warrant mentioning, and further investigations are needed. Proximal variables in the HLE were estimated based on parental questionnaires and included items about shared book reading with children and children’s independent print exposure. Prior studies have included items that query direct teaching activities, such as whether parents formally teach children about pronunciation, spelling, writing, and the like, as well as literacy resources in the home, which has been indexed by the number of children’s books available in the home environment (Georgiou et al., 2021; Inoue et al., 2018a). Parent teaching and literacy resources have previously been shown to have effects on children's reading development that are unique from the contributions of parental SES and shared book reading. (Hamilton et al., 2016; Inoue et al., 2018; see also Puglisi et al., 2017). In the current study, parental SES was used as a distal indicator of the home structural environment. Other components of the home socioeconomic conditions included in prior studies are income-to-needs ratio and food insecurity (e.g., McNeilly et al., 2021; K. G. Noble et al., 2005). Previous studies have used a composite score of parental level of educational attainment and income-to-needs ratio to represent a fuller picture of the home socioeconomic conditions and influences on children's academic achievement (e.g., Dilworth-Bart, 2012). A number of studies have shown that food insecurity and other metrics of resource scarcity are inter-related with other SES factors, as well as similarly show substantial associations with children's EFs and language abilities (Ellwood-Lowe et al., 2022; McNeilly et al., 2021). However, future studies should consider how other SES metrics, as well as other learning activities in the home environment (e.g., math; Wirth et al., 2022) may relate to children's EFs and academic outcomes. Additionally, future studies should consider capturing the rich variation in the home cognitive environment and socioeconomic circumstances to identify variables that could explain the remaining variance between parental SES and children's WR skills observed in the current study (even after controlling for the HLE and children's EFs).

# CHAPTER 3

## Study 2: The home environment and neurocognitive systems

### Motivation

The aim for **Study 2** was to understand how the HLE and parental SES influence children's cognitive development by affecting the underlying neural systems. In the previous study, findings revealed that while these home factors were both related to children's reading outcomes, including WR skills, they also had unique associations with top-down cognitive abilities. Uniquely from parental SES, the HLE was related to children's OL abilities; uniquely from the HLE, parental SES was associated with children's EFs. Given these distinct patterns of associations, the neural mechanisms underlying the influences of the HLE and parental SES should also differ. Here, brain imaging was used to examine the extent to which the HLE and parental SES relate to children's brain anatomy and in turn, behavioral measures of language and executive abilities.

Aside from its genetic blueprint, brain development is built on environmental inputs—such as those present in the HLE and/or linked to parental SES. The pace of brain development has been distinguished between fundamental sensory versus high-level association cortices, which has implications for vulnerability and resilience across the range of environmental influences (Tooley et al., 2021). Here, the focus is on the period of middle childhood and school age because this window allows a close look at the neurocognitive correlates of children's reading development (Chyl et al., 2021; Saygin et al., 2016). As discussed in the introduction, some neurocognitive correlates of reading include the occipital-temporal regions implicated in WR skills, the temporal-parietal regions implicated in OL abilities, and the prefrontal-EF system. These different neurocognitive systems enable an examination of the extent to which the HLE and parental SES relate children's brain development, and in turn behavioral outcomes, that is, WR skills, OL abilities, and EFs.

Environmental inputs are thought to impact anatomical brain differences in children via experience-driven neural plasticity. Two indices of the brain anatomy are cortical thickness and surface area, which together compose the gray matter cortex (Brito & Noble, 2014; Schnack et al., 2015). Variation in the cortical thickness is believed to be driven by asymmetrical division in stem cells, as well as dendritic growth and synaptogenesis (Rakic, 1995). While the cortex thickens before two years of age, the cortex undergoes widespread thinning starting between two and five years of age and continuing thereafter into adulthood (Tooley et al., 2021). Postponed thinning via synaptic pruning and pronounced thickening via myelination are thought to correspond with variation in cognitive abilities (Schnack et al., 2015). Surface area is thought to be largely driven by symmetrical division in stem cells, as well as cortical folding and the pressure from cortical compartments underneath pushing the layers above outward (Rakic, 1995). Surface area appears expand throughout early adolescence and then shrinks across middle adulthood (Tamnes et al., 2017). Regional expansion in surface area is thought to accommodate the increases in neuronal composition and involvement in cognitive functioning (Schnack et al., 2015). Increased cortical thickness and/or surface area have been shown to positively predict children's language and executive abilities (Asaridou et al., 2017; Fjell et al., 2012; Tadayon et al., 2020; Tamnes et al., 2010). Environmental inputs are hypothesized to shape neural anatomy—and consequently, function—by pruning the initially over-produced synaptic connections via the process of *selective elimination* (Changeux & Danchin, 1976). Limited environmental inputs are thought to relate to early or over-pruning of synaptic connections or weakened dendritic branching, thus resulting in reduced cortical thickness and less surface area (Bennett et al., 1974; M. C. Diamond et al., 1975).

## Links between the home environment and neurocognitive systems

### The home environment and the occipital-temporal cortex

The HLE has been linked to the occipital-temporal regions implicated in WR skills. The HLE includes print-focused activities, i.e., activities that expose children to the written language system, spelling patterns, and grapheme-phoneme correspondence (Sénéchal, 2006; Sénéchal & LeFevre, 2002). One study has shown that the HLE predicts activity in children's bilateral occipital-temporal regions during a phonological processing task (Powers et al., 2016). In this same study, the HLE was also shown to predict activity in the left inferior frontal gyrus and right superior temporal gyrus during the phonological processing task (Powers et al., 2016). Lying within the ventral visual stream, the left-lateralized occipital-temporal cortex encompasses the visual word form area (or fusiform gyrus), which has been shown to facilitate rapid visual WR (McCandliss et al., 2003). The inferior frontal and superior temporal gyri have been implicated in phonological perception and lexico-semantic functions, which have also been shown to be involved in WR (Joseph et al., 2001; Turkeltaub et al., 2002). Of note, these studies carefully controlled for parental SES, thus showing the unique associations between the HLE and regions within the brain reading (occipital-temporal) network.

Parental SES has been linked to the occipital-temporal regions implicated in WR skills (Joseph et al., 2001; K. G. Noble et al., 2006). Parental SES has previously been used as a marker for the availability of and access to sociocultural opportunities, cognitive resources, and other proximal variables that could enhance the environment surrounding children's neurocognitive development (Antonoplis, 2022; Berkowitz et al., 2017; Dearing et al., 2001; Magnuson et al., 2009). One study has shown that parental SES modulates the relation between children's phonological awareness and activity in the left occipital-temporal cortex during a visual word recognition task (K. G. Noble et al., 2006). This study showed that the association between phonological awareness and decoding-related brain regions was greater among children from lower socioeconomic background (K. G. Noble et al., 2006). Another study has revealed that children with higher parental SES backgrounds show a positive association between the left inferior longitudinal fasciculus and WR skills, while peers from lower parental SES circumstances exhibited a positive relation between the right inferior longitudinal fasciculus and WR skills (Gullick et al., 2016). The inferior longitudinal fasciculus is a white-matter tract that runs along the inferior temporal and occipital-temporal cortices; it has been implicated in reading (on the left hemisphere) and general visual processes (on the right hemisphere) (Centanni et al., 2018; Yeatman et al., 2013). One study showed that even after controlling for the HLE, parental SES was associated with diffusion in the inferior longitudinal fasciculus, which in turn predicted children's WR skills (Ozernov-Palchik et al., 2021). It is possible that parental SES impacts the neurocognitive processes subserved by the occipital-temporal regions in ways that influence children's WR skills.

### The HLE and the temporal-parietal cortex

The HLE has been related to the temporal-parietal regions implicated in OL abilities. In addition to print-focused opportunities, the HLE includes meaning-focused activities, like shared book reading, that when present are considered beneficial to children's OL development (Sénéchal, 2006; Sénéchal & LeFevre, 2002). Studies have shown that the HLE predicts activity in children's extended language networks during story listening tasks, including the lateral temporal and auditory association cortices (e.g., temporal pole, as well as superior and middle temporal gyri), inferior parietal lobule (e.g., angular gyrus), and the posterior cingulate cortex (Hutton et al., 2015, 2017). The superior temporal gyrus is an important part of the auditory system that facilitates word form detection and segmentation of phonological cues (Cohen et al., 2004; Mesgarani et al., 2014). This primary sensory cortex relays auditory information to higher-order language hubs like the lateral temporal cortex to process lexico-semantic aspect of word stimuli and complex syntax, as well as the angular gyrus (in the inferior parietal lobule) to enable discourse mentalizing and linguistic comprehension (Friederici, 2011; Wilson et al., 2008).

The link between parental SES and brain regions implicated in OL abilities may be explained through its shared variance with the HLE. Some reports have suggested that proximal language activities mediate the link between parental SES and the development of children's brain language system (Merz et al., 2020; Romeo et al., 2018; see also Pace et al., 2017). In these studies, parental SES was shown to associate with taking turns in conversation between parent and child at home, which in turn predicted differences in the anatomy and function of the inferior frontal gyrus and superior temporal gyrus (Merz et al., 2020; Romeo et al., 2018). As previously mentioned, the inferior frontal gyrus and superior temporal gyrus are implicated in phonological awareness and lexico-semantic demands in word stimuli (Friederici, 2011; Joseph et al., 2001; Turkeltaub et al., 2002; Wilson et al., 2008). These findings appear to overlap with the aforementioned results that showed that the HLE was related to not only the inferior frontal gyrus and superior temporal gyrus implicated in reading skills, but also the temporal-parietal regions involved in complex language processes. The HLE offers a rich source of proximal language activities and parent-child interactions that in part are linked to parental SES; studies have yet to control for the HLE to examine to what extent parental SES relates to the neural correlates of children's OL abilities.

### Parental SES and the prefrontal-executive system

Parental SES has been associated with children's prefrontal-EF system. The prolonged development of the prefrontal-executive system is believed to make it particularly susceptible to variables and experiences associated with parental SES (Kolb et al., 2012; Tooley et al., 2021). Parental SES has been shown to predict differences in the anatomy and function of the prefrontal areas implicated in EFs (Finn et al., 2017; Lawson et al., 2013; Shaked et al., 2018; Sheridan et al., 2012). Of note is that parental SES appears to have the most pronounced impacts on children's EFs and language abilities as compared to other cognitive abilities, suggesting that these measures could share a substantial amount of overlapping variance (K. G. Noble et al., 2005; Romeo et al., 2022; Weiland et al., 2014). One way to gain clarity and potentially reveal a unique relation between parental SES and the prefrontal-EF system is by simultaneously considering the HLE and SES and their associations with the language-supporting regions.

## Current study

The current study aims to elucidate the extent to which the HLE and parental SES relate to children's brain anatomy and, in turn, language and executive abilities. Anatomical brain measurements were first used to identify which regions are affected by the HLE and parental SES, and then among these affected regions, examine which ones predict differences in children's WR, OL, and EF abilities. To this end, mediation analyses were conducted with behavioral indices of children's WR skills, OL abilities, and EFs, correlating them with anatomical brain indices as a way to demarcate these different neurocognitive systems. The following three hypotheses were tested:

- ***Hypothesis 1***. Controlling for parental SES, the HLE will predict anatomical differences in the occipital-temporal regions, which in turn will predict WR skills.
- ***Hypothesis 2***. Uniquely from parental SES, the HLE will relate to anatomical differences in the temporal-parietal regions, which in turn will predict OL abilities.
- ***Hypothesis 3***. After accounting for the HLE, parental SES will be correlated with anatomical differences in the prefrontal regions, which in turn will predict EFs.

## Methods

### Sample

A subsample of participants with brain imaging data were drawn from the same cohort of subjects included in Study 1 (**Chapter 2**).

### Brain imaging

#### *Acquisition and preprocessing*

When children visited the laboratory for behavioral assessments, they also underwent anatomical brain imaging ($N$ = 162). For each participant, a T1-weighted anatomical MR image was acquired using a Phillips Achieva 3-Tesla scanner, with a 32-channel head coil, for a multi-shot, magnetization-prepared gradient recalled echo scanning sequence (Mugler & Brookeman, 1990). Scan parameters were as follows: field of view = 256-mm$^2$ resolution, 176 slices; slice thickness/gap = 1/0 mm; repetition time = 9.051s; echo time = 4.61s; flip angle = 8$^o$; voxel size = 1-mm$^3$ isotropic; and acquisition time = 274s. All images were processed using FreeSurfer preprocessing steps via a semi-automated processing stream (*recon-all* function) as previously described in standardized protocols (Dale et al., 1999; Fischl et al., 1999). These steps included motion correction and image normalization, removal of non-brain tissue, spatial smoothing, and construction of white/gray matter and gray matter/cerebrospinal fluid boundaries.

#### *Anatomical brain measurement*

All processed anatomical MR images underwent quality-control procedures, including detection of motion-associated artifacts (although, the T1-weighted sequence was optimized to minimize these irrelevant motions in real time), brain segmentation errors, and assurance of accurate mapping of the pial and white matter surfaces. Sixteen scans were removed due to a high volume of artifacts (Reuter et al., 2015), incomplete scan acquisition, or failure during the preprocessing steps, leaving the final $N$ = 146 scans for analyses. Processed brain surfaces from all participants underwent atlas-based registration and parcellation (Glasser et al., 2016; van Essen et al., 2012), and resampled into a common space (*fsaverage* in FreeSurfer). In this study, cortical thickness and surface area were used as indices of the gray mater cortex. To account for overall brain size, estimated intracranial volume was treated as a covariate in analyses (Buckner et al., 2004).

## Analyses

### *Whole brain analyses*

Univariate regressions were conducted to examine the relations between indicators of the home environment (HLE and SES) and structural brain indices (cortical thickness and surface area). For each anatomical index, multiple regressions included both HLE and SES as the predictors in order to isolate their unique predictions. Covariates were included to control for background variables such as parents' reading history and children's age, handedness, biological sex, perceptual IQ, and school information, as well as their intracranial volume. Using the *lm.boot()* function, significance levels were determined by bootstrapping simulation-based 95% confidence intervals across 10,000 interactions, which were free of any distributional assumptions. Regional findings were reported after using the *p.adjust()* function to perform correction for multiple comparisons with the false discovery rate approach at $p < 0.05$.

### *Regional mediation analyses*

Regional findings from univariate regressions were included in mediation analyses to evaluate the relations between indicators of the home environment (the HLE and parental SES), anatomical brain indices, and cognitive measures (WR skills, OL abilities, and EFs). For each anatomical index, mediation analyses treated one of the three cognitive measures as the dependent variable while also controlling for the other two in order to isolate unique associations, thus resulting in mediation analyses predicting: WR controlling for OL and EF; OL controlling for EF and WR; and EF controlling for WR and EF. Average causal mediation (indirect) effects were estimated based on the associations between HLE or SES and brain indices, and then between brain indices and cognitive abilities. Significance levels were determined by a permutation approach implemented in the *mediate()* function. Findings were reported after performing correction for multiple comparisons using the Bonferroni approach at $p < 0.05$.

## Results

Descriptive statistics of the current sample can be found in **Table 3.1**, which includes information on background variables collected [at baseline] from parents (reading history) and children (age, biological sex, school information [Title 1 Status], and perceptual reasoning), as well as home environment indicators (the HLE and parental SES), and measures of children's WR skills, OL abilities, EFs, and RC outcomes.

**Table 3.1**. Descriptive statistics for the current sample ($N = 146$).

| | | ***M*** | ***SD*** | ***Min*** | ***Max*** |
|---|---|---|---|---|---|
| **Parent surveys** | | | | | |
| 1 | Reading History | 27.95 | 12.83 | 2 | 65 |
| 2 | SES, parental education | 6.15 | 0.80 | 4 | 7 |
| 3 | HLE | 3.11 | 1.12 | 0 | 5 |
| a | RQ 1, shared reading | 3.33 | 1.13 | 0 | 5 |
| b | RQ 2, print exposure | 2.88 | 1.52 | 0 | 5 |
| **Child variables** | | | | | |
| ***Demographic information*** | | | | | |
| 4 | Age (after 1st grade) | 7.47 | 0.37 | 6.42 | 8.33 |
| 5 | Sex | 79 (54%) girls | | | |
| 6 | Handedness | 43.82 | 47.08 | -90 | 100 |
| 7 | Perceptual IQ | 53.00 | 8.67 | 29 | 80 |
| 8 | School (Title 1 Status) | 20 (14%) attended | | | |
| ***WR skills*** | | | | | |
| 9 | WJ Basic Reading | 107.89 | 13.04 | 70 | 136 |
| 10 | TOWRE Total Reading Efficiency | 101.81 | 15.49 | 64 | 133 |
| ***OL abilities*** | | | | | |
| 11 | TOWK Receptive Vocabulary | 12.79 | 2.59 | 6 | 17 |
| 12 | WASI Vocabulary | 53.99 | 10.76 | 28 | 79 |
| 13 | Narrative Text Listening Comp. | 4.31 | 1.61 | 1 | 8 |
| 14 | Expository Text Listening Comp. | 6.57 | 1.17 | 3 | 8 |
| ***EFs*** | | | | | |
| 13 | NEPSY Animal Sorting | 9.26 | 3.47 | 1 | 18 |
| 14 | WMTB Listening Recall | 98.54 | 19.38 | 11 | 134 |

### *Preliminary findings*

Pairwise correlations among background variables, as well as composite scores from measures of interest were calculated. Composite scores were used in regional mediation analyses. (See **Table 3.2**.

**Table 3.2**. Pairwise correlations among the collected measures and surveys (*N* = 146).

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Parent surveys** | | | | | | | | | | | | |
| 1 | Reading history | - | | | | | | | | | | |
| 2 | SES, parental education | **-0.189** | - | | | | | | | | | |
| 3 | HLE | **-0.298** | **0.300** | - | | | | | | | | |
| **Child variables** | | | | | | | | | | | | |
| ***Demographic information*** | | | | | | | | | | | | |
| 4 | Age | 0.015 | 0.005 | -0.059 | - | | | | | | | |
| 5 | Biological sex | -0.050 | -0.053 | **-0.144** | 0.131 | - | | | | | | |
| 6 | Handedness | 0.108 | 0.135 | -0.008 | 0.020 | -0.035 | - | | | | | |
| 7 | Perceptual IQ | -0.094 | **0.237** | 0.126 | 0.010 | **-0.177** | 0.062 | - | | | | |
| 8 | School (Title 1 Status) | 0.091 | **-0.266** | **-0.158** | -0.050 | 0.073 | 0.058 | -0.092 | - | | | |
| ***Behavioral measures*** | | | | | | | | | | | | |
| 9 | WR skills | **-0.263** | **0.453** | **0.324** | -0.071 | -0.086 | -0.097 | **0.256** | **-0.203** | - | | |
| 10 | OL abilities | **-0.164** | **0.400** | **0.360** | 0.177 | -0.076 | 0.009 | **0.450** | **-0.259** | **0.416** | - | |
| 11 | EFs | -0.101 | **0.350** | **0.220** | 0.056 | **-0.210** | 0.166 | **0.435** | **-0.144** | **0.419** | **0.456** | - |

*Note*. Coefficients in **bold** met $p < 0.05$.

Correlations between variables showed that the HLE and parental SES were positively correlated ($r = 0.300$, $p < 0.05$). The HLE was positively correlated with WR skills ($r = 0.324$), OL abilities ($r = 0.30.$), and EFs ($r = 0.220$) (all $p$'s $< 0.05$). Parental SES was positively correlated with WR skills ($r = 0.453$), OL abilities ($r = 0.400$), and EFs ($r = 0.350$) (all $p$'s $< 0.05$).

### Home Environment Indicators and Differences in the Brain Cortical Thickness

#### ***The HLE predictions*** (**Figure 3.1** a)

Controlling for parental SES, the HLE was found to be positively associated with differences in the cortical thickness of bilateral inferior frontal gyri, bilateral auditory association cortices (superior and middle temporal gyri), right lateral temporal cortex, left inferior parietal lobule, left temporal-parietal cortex, bilateral occipital-temporal gyri, and bilateral posterior cingulate cortices.

#### ***Parental SES predictions*** (**Figure 3.1** b)

Controlling for the HLE, SES was found to be associated with differences in the cortical thickness of bilateral prefrontal cortices (spanning the lateral and medial portions), right precentral gyrus, bilateral inferior frontal gyri, left auditory association (superior temporal cortex), left medial temporal gyrus (hippocampus), bilateral superior parietal lobules, and bilateral occipital-temporal cortices.

### Home Environment Indicators and Differences in the Brain Surface Area

#### ***The HLE predictions*** (**Figure 3.2** a)

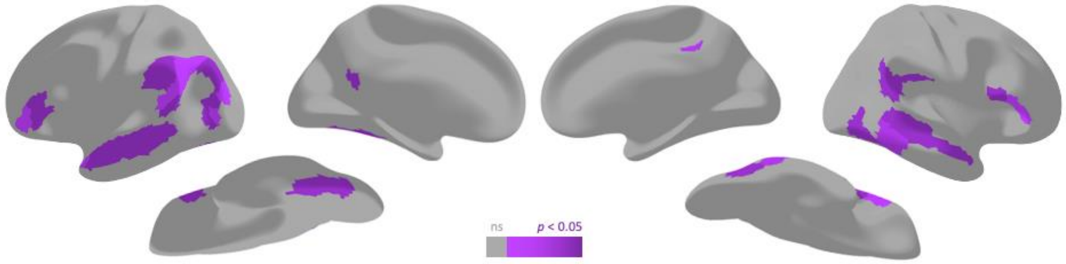
Controlling for SES, the HLE was found to be associated with differences in the surface area of right inferior frontal gyrus, right precentral gyrus, bilateral auditory and auditory association cortices (superior and middle temporal gyri), bilateral lateral temporal cortices (temporal pole and inferior temporal gyrus), bilateral inferior parietal lobules, and right occipital-temporal cortex.

#### ***Parental SES predictions*** (**Figure 3.2** b)

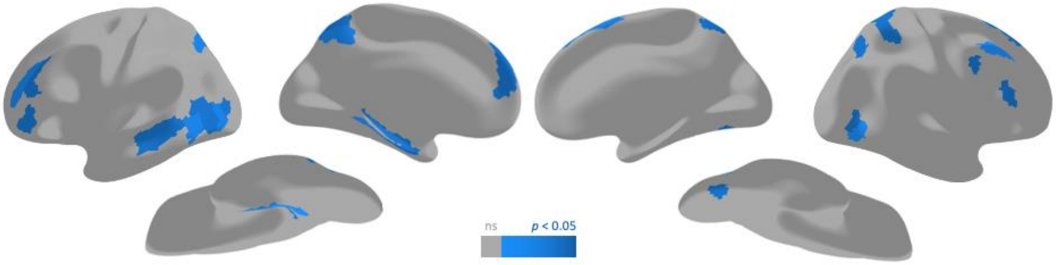
Controlling for the HLE, SES was found to be associated with differences in the surface area of right medial prefrontal cortex, left inferior frontal gyrus, right medial temporal cortex (hippocampus), bilateral superior parietal lobules, and right occipital-temporal cortex

**Figure 3.1**. Cortical thickness differences predicted by the HLE and parental SES.

a) The HLE predictions.



b) Parental SES predictions.



c) Common findings between the HLE and parental SES.

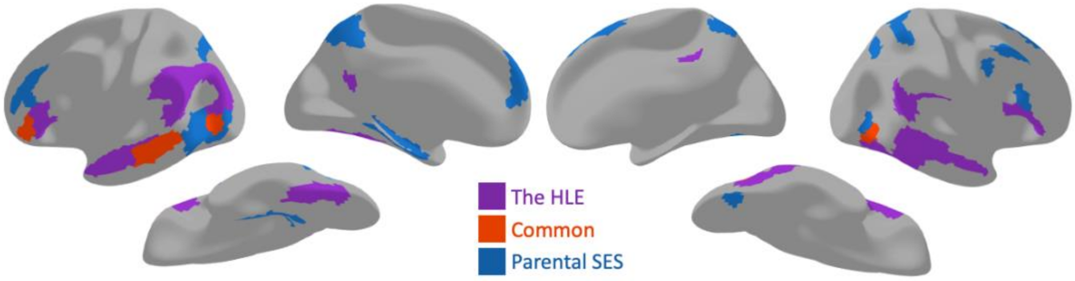
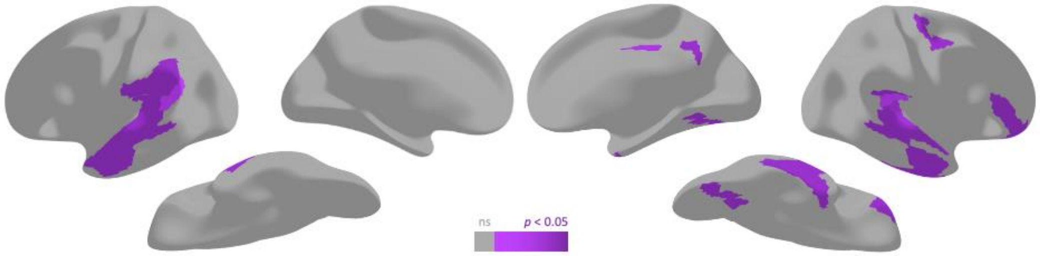
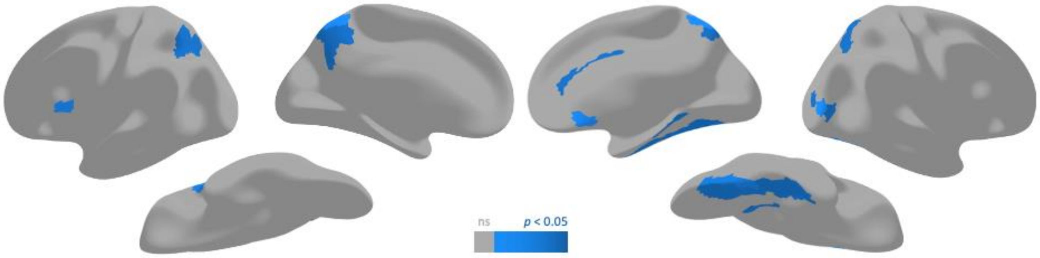


**Figure 3.2**. Surface area differences predicted by the HLE and parental SES.

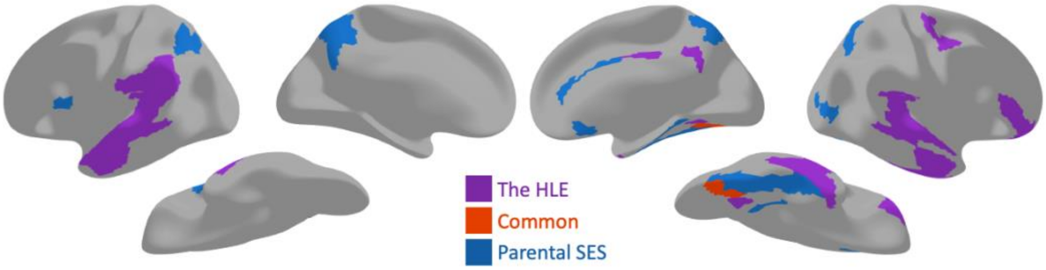
a) The HLE predictions.



b) Parental SES predictions.



c) Common findings between the HLE and parental SES.



## Home Environment Indicators, Regional Cortical Thickness, and Behavioral Measures

### ***The HLE predictions*** (**Figure 3.3** and **Table 3.3**)

#### **WR skills**.

The relation between the HLE and WR skills was shown to be mediated by differences in the cortical thickness of the left occipital-temporal cortex ($b = 0.015$, $p < 0.05$).

#### **OL abilities**.

The relation between the HLE and OL abilities was shown to be mediated by differences in the cortical thickness of the left inferior parietal lobule ($b = 0.019$, $p < 0.05$).

#### **EFs**.

No unique findings reached significance for the relations between the HLE, regional cortical thickness, and EFs ($p > 0.05$).

### ***Parental SES predictions*** (**Figure 3.4** and **Table 3.3**)

#### **WR skills**.

No unique findings reached significance for the relations between parental SES, regional cortical thickness, and WR skills ($p > 0.05$).

#### **OL abilities**.

The relation between parental SES and OL abilities was shown to be mediated by differences in the cortical thickness of the left medial temporal cortex ($b = 0.015$, $p < 0.05$).

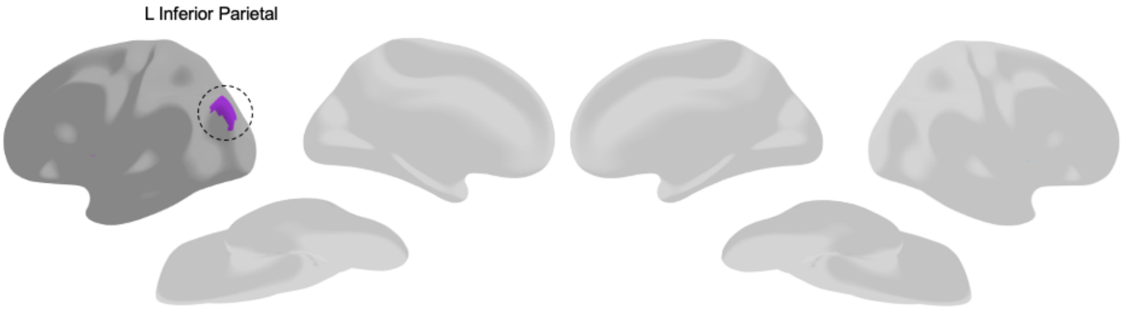
#### **EFs**.

The relation between parental SES and EFs was shown to be mediated by differences in the cortical thickness of the left occipital-temporal cortex ($b = 0.033$), as well as the right dorsolateral prefrontal and occipital-temporal cortices ($b$'s = 0.028 & 0.022, respectively) (all $p$'s < 0.05).

**Figure 3.3**. The HLE, regional cortical thickness, and behavioral measures.

(a) WR skills.

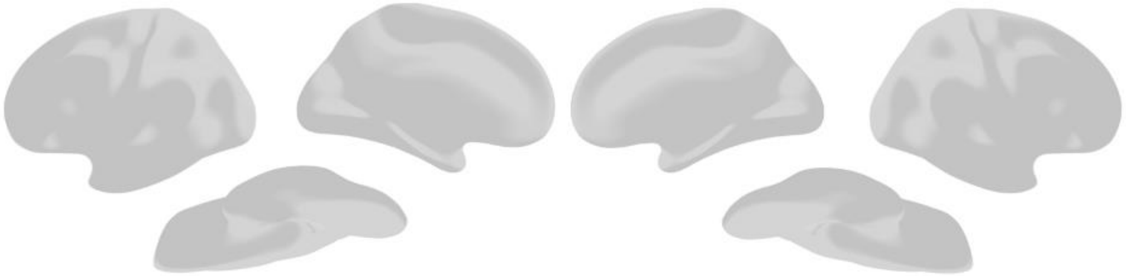
(b) OL abilities.



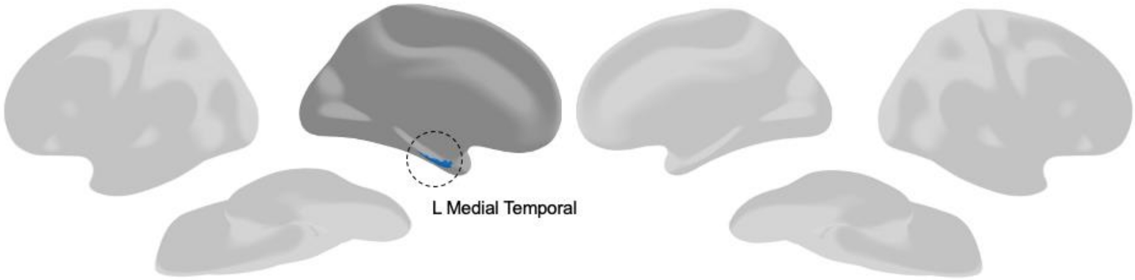
(c) EFs.

**Figure 3.4**. Parental SES, regional cortical thickness, and behavioral measures.

(a) WR skills.



(b) OL abilities.



(c) EFs.

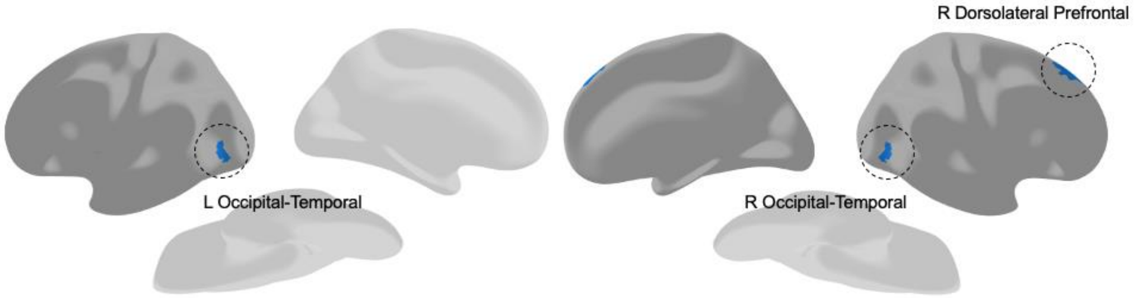
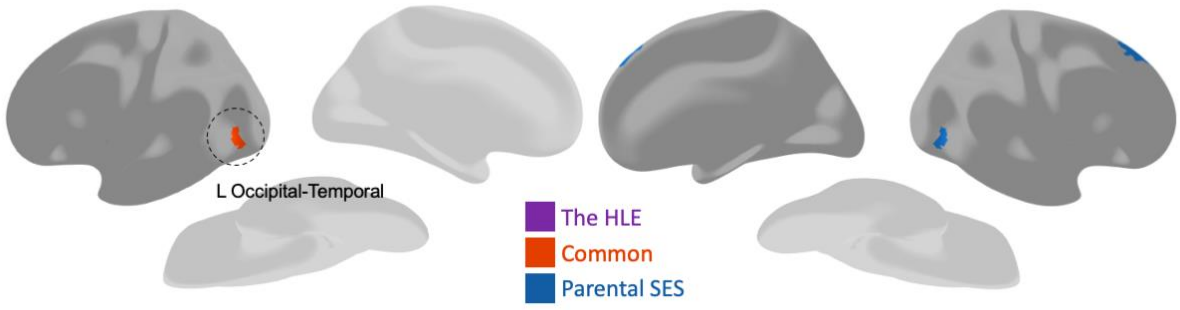


**Table 3.3**. Summary findings for regional cortical thickness and behavioral measures.

| **Contrast** | **Region** | ***b*** | ***Cis*** | **%** |
|---|---|---|---|---|
| **The HLE predictions** | | | | |
| → WR skills | - | | | |
| → OL abilities | L Inferior Parietal Lobule | 0.019 | (0.008, 0.030) | 19% |
| → EFs | L Occipital-Temporal Cortex [a] | 0.015 | (0.008, 0.022) | 30% |
| **Parental SES predictions** | | | | |
| → WR skills | - | | | |
| → OL abilities | L Medial Temporal Cortex | 0.015 | (0.007, 0.023) | 11% |
| → EFs | L Occipital-Temporal Cortex [a] | 0.033 | (0.014, 0.053) | 19% |
| | R Dorsolateral Prefrontal Cortex | 0.028 | (0.016, 0.040) | 22% |
| | R Occipital-Temporal Cortex | 0.022 | (0.013, 0.031) | 18% |

*Note*. Indirect effects (*b*) were presented below with 95% confidence intervals (*CI*s) and the proportion of the total effect mediated (%). All indirect effects met $p < 0.05$. [a] denoted common finding between the HLE and parental SES predictions.

**Figure 3.5**. Common findings between the HLE and parental SES, regional cortical thickness, and EFs.



## Home Environment Indicators, Regional Surface Area, and Behavioral Measures

### *The HLE predictions* (**Figure 3.5** and **Table 3.4**)

#### **WR skills**.

The relation between the HLE and WR skills was shown to be mediated by differences in the surface area of the left inferior parietal lobule ($b = 0.021$), as well as the right ventral visual cortex and inferior frontal gyrus ($b$'s = 0.032 and 0.025, respectively) (all $p$'s < 0.05).

#### **OL abilities**.

The relation between the HLE and OL abilities was shown to be mediated by differences in the surface area of the bilateral auditory association cortices ($b$'s = 0.017 and 0.014, respectively; both $p$'s < 0.05).

#### **EFs**.

No unique findings reached significance for the relations between the HLE, regional surface area, and EFs ($p > 0.05$).

### *Parental SES predictions* (**Figure 3.6** and **Table 3.4**)

#### **WR skills**.

The relation between parental SES and WR skills was shown to be mediated by differences in the surface area of the right ventral visual cortex ($b = 0.021$, $p < 0.05$).

#### **OL abilities**.

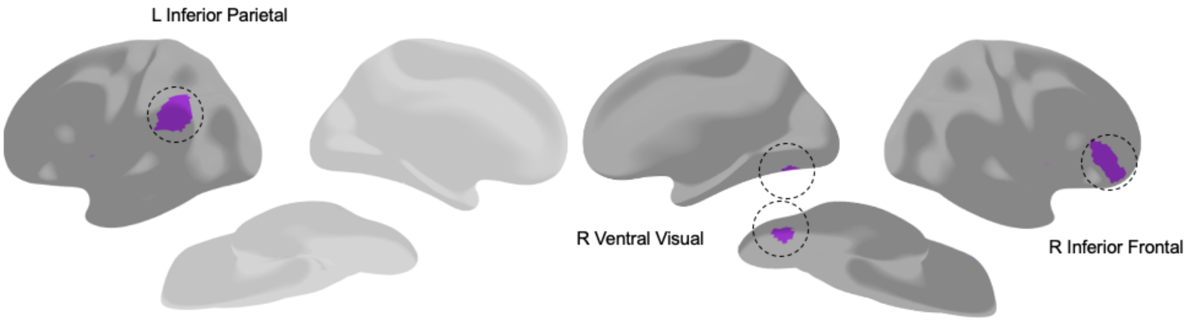
The relation between parental SES and OL abilities was shown to be mediated by differences in the surface area of the right medial temporal cortex ($b = 0.017$, $p < 0.05$).

#### **EFs**.

The relation between parental SES and EFs was shown to be mediated by differences in the surface area of the bilateral superior parietal cortices ($b$'s = 0.014 and 0.018, respectively; both $p$'s < 0.05), and the right ventral visual cortex ($b = 0.010$, $p < 0.05$).

**Figure 3.6**. The HLE, regional surface area, and behavioral measures.

(a) WR skills.

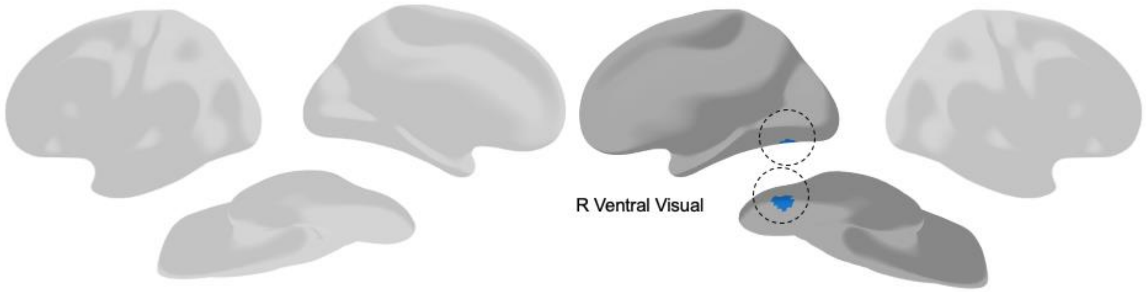


(b) OL abilities.

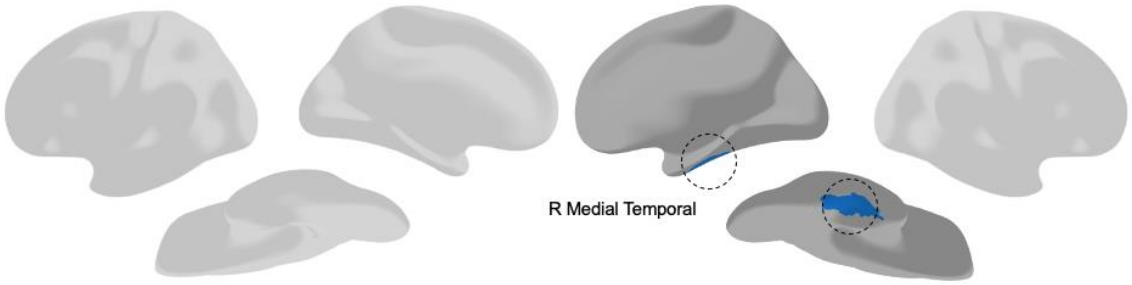
(c) EFs.

**Figure 3.7**. Parental SES, regional surface area, and behavioral measures.

(a) WR skills.



(b) OL abilities.



(c) EFs.

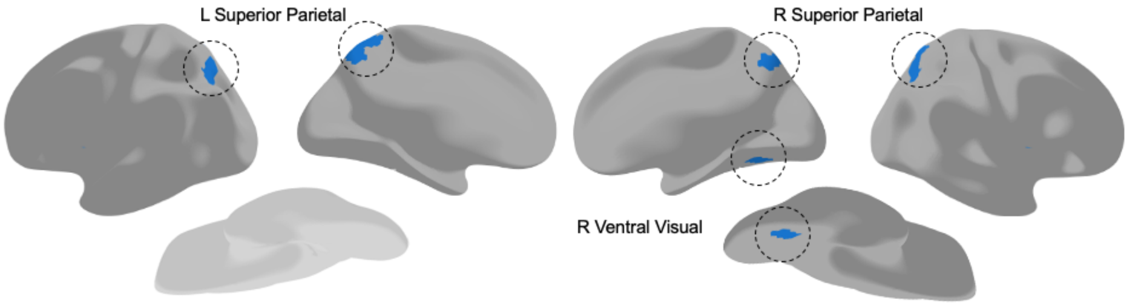
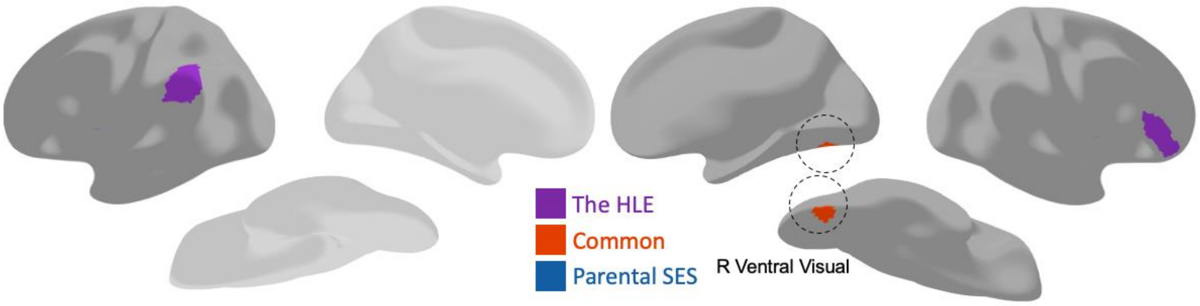


**Table 3.4**. Summary findings for regional surface area and behavioral measures.

| Contrast | Region | *b* | *Cis* | % |
|---|---|---|---|---|
| **The HLE predictions** | | | | |
| → WR skills | L Inferior Parietal Lobule | 0.021 | (0.010, 0.030) | 11% |
| | R Inferior Frontal Gyrus | 0.025 | (0.011, 0.050) | 12% |
| | R Ventral Visual Cortex [a] | 0.032 | (0.007, 0.057) | 12% |
| → OL abilities | L Auditory Association Cortex | 0.017 | (0.009, 0.025) | 8% |
| | R Auditory Association Cortex | 0.014 | (0.008, 0.019) | 11% |
| → EFs | - | | | |
| **Parental SES predictions** | | | | |
| → WR skills | R Ventral Visual Cortex [a] | 0.021 | (0.002, 0.040) | 18% |
| → OL abilities | R Medial Temporal Cortex | 0.017 | (0.005, 0.028) | 13% |
| → EFs | L Superior Parietal Lobule | 0.014 | (0.002, 0.026) | 16% |
| | R Superior Parietal Lobule | 0.018 | (0.001, 0.035) | 8% |
| | R Ventral Visual Cortex | 0.010 | (0.003, 0.018) | 8% |

*Note*. Indirect effects (*b*) were presented below with 95% confidence intervals (*CI*s) and the proportion of the total effect mediated (%). All indirect effects met $p < 0.05$. [a] denoted common finding between the HLE and parental SES predictions.

**Figure 3.8**. Common findings between the HLE and parental SES, regional surface area, and WR skills.



## Discussion

The aim for **Study 2** was to examine the extent to which the HLE and parental SES relate to anatomical brain differences in children and, in turn, their WR, OL, and EF abilities. Whole-brain results revealed that both the HLE and parental SES overlapped on differences in the cortical thickness of the left inferior frontal and auditory association cortices, and bilateral occipital-temporal cortices, as well as surface area of the right ventral visual cortex (**Figure 3.1** c and **Figure 3.2** c). However, the HLE appeared to uniquely track with the temporal auditory and inferior parietal cortices, whereas parental SES was associated with the lateral prefrontal and superior parietal cortices. Mediation analyses were also conducted to reveal the extent to which the HLE and parental SES relate to children's WR skills, OL abilities, and EFs through anatomical differences in these brain regions. The HLE and parental SES were commonly associated with the surface area of right ventral visual cortex and, in turn, WR skills. Controlling for parental SES, the HLE was related to the surface area of the left inferior parietal lobule and right inferior frontal gyrus and, in turn, WR skills. Uniquely from parental SES, the HLE was related to the cortical thickness of the left inferior parietal lobule, as well as surface area of the bilateral auditory association cortices and, in turn, OL abilities. Controlling for the HLE, parental SES was related to the cortical thickness and surface area of the medial temporal gyri and, in turn, OL abilities. Adjusting for the HLE, parental SES was associated with the cortical thickness of the right prefrontal and occipital-temporal cortices, as well as surface area of the bilateral superior parietal lobules and right ventral visual cortex and, in turn, EFs. The HLE and parental SES were commonly associated with the cortical thickness of the left occipital-temporal cortex and, in turn, EFs.

### The home environment and children's WR skills

The common findings on WR skills between the HLE and parental SES findings was observed in the surface area the right ventral visual regions, which includes the posterior portion of the occipital-temporal cortex. The ventral visual cortex includes a set of brain regions involved in processing visual stimuli (Amso & Scerif, 2015; Gilbert & Li, 2013). One study has shown that controlling for parental SES, the HLE predicts activity in both the left and right occipital-temporal cortices during a phonological awareness task (Powers et al., 2016). Another study has suggested that children from higher- versus lower-SES backgrounds leverage left versus right occipital-temporal cortices to support reading outcomes, respectively (Gullick et al., 2016). The involvement of the right occipital-temporal cortex has been posited to underlie a neural compensatory mechanism in reading processes, particularly among children who struggle with reading (Hoeft, Meyler, et al., 2007). In particular, one study found that at the pre-reading stage, children who would develop reading difficulties later showed reduced surface area in bilateral occipital-temporal cortices (Beelen et al., 2019). The right occipital-temporal cortex has also been thought to support general visual processes relevant in early developmental stages of reading skills prior to depending on the classical left occipital-temporal region in mature reading (Booth et al., 2003; Centanni et al., 2017; Church et al., 2008). Prior reports have suggested that surface area expansion in sensory-specific association cortices, including the occipital-temporal regions, could reflect the expansion and reorganization of the underlying sensory visual-auditory topographic maps in response to increased experience (Lyall et al., 2015; Pienkowski & Eggermont, 2011). The current findings suggest that the HLE and parental SES interact with the visual processes subserved by the right ventral visual cortex in ways that influence children's WR skills.

Uniquely from parental SES, the HLE appeared to relate to children's WR skills through the surface area of left inferior parietal lobule (centrally, the supramarginal gyrus) and the right inferior frontal gyrus. The left supramarginal gyrus in the inferior parietal lobule have been shown to contribute to the phonological aspect of word processing (Hartwigsen et al., 2010; Stoeckel et al., 2009). Some findings attribute the involvement of inferior frontal gyrus in WR to speech-sound parsing (Joseph et al., 2001; Turkeltaub et al., 2002). Other studies have shown that decoding written word activates visual cortices that then relay information to the inferior parietal lobule, where visual word forms are recognized (Cao et al., 2008). The inferior frontal gyrus is thought to support a range of lexico-semantic functions, especially at the word level (C. J. Price, 2012; Richlan, 2012). While previous studies have largely reported the left-lateralized contribution of the inferior frontal gyrus in WR skills, the right-hemisphere homologue is thought to underlie compensatory functions to support efficient reading (Aboud et al., 2018; Farris et al., 2011; Hoeft et al., 2011). Prior reports have suggested that extended periods of surface area expansion in cortical regions supporting high-order cognition, including the inferior frontal gyrus and inferior parietal lobule, could lead to increased neural connectivity and more efficient computational power (Sydnor et al., 2021; Tooley et al., 2021). The current findings showing the relations between the HLE, differences in the surface area of the inferior parietal lobule and inferior frontal gyrus, and

WR skills also align with a recent study that used diffusion imaging (Davison et al., 2023). That study observed a positive relation between the HLE and left lateralization of the superior longitudinal fasciculus, a tract that connects the inferior frontal gyrus and inferior parietal lobule (Davison et al., 2023). Further, the HLE and lateralization of the superior longitudinal fasciculus measured at kindergarten were shown to predict children's second-grade reading outcomes (Davison et al., 2023).

### The home environment and children's OL abilities

Uniquely from parental SES, the HLE predicted children's OL abilities through the surface area of the bilateral auditory association cortices, including superior and lateral temporal regions, as well as the cortical thickness of left inferior parietal lobule (centrally, the angular gyrus). The auditory association cortex, especially the superior temporal gyrus, has been associated with sound perception and sentence comprehension (Cohen et al., 2004; Friederici, 2011; Mesgarani et al., 2014). The angular gyrus in the inferior parietal lobule has been attributed to semantic aspect of word processing, as well as comprehension and meaning making (A. R. Price et al., 2015; Seghier, 2013; Spreng & Andrews-Hanna, 2015). One study has shown that after controlling for parental SES, parent-child language interactions relate to the surface area of the left superior temporal gyrus and, in turn, reading outcomes. It is possible that language inputs, in parent-child interactions and the HLE, stimulate neuronal properties in the superior temporal gyrus that yield surface area expansion. Using functional brain imaging, past studies have shown that the HLE predicts differences in the involvement of the temporal-parietal language system, including the superior temporal and angular gyri, during story-listening tasks (Hutton et al., 2015, 2017). Language inputs from the HLE could relate to expansion and reorganization of the underlying auditory tonotopic map represented in the superior temporal gyrus (Lyall et al., 2015; Pienkowski & Eggermont, 2011). The superior temporal gyrus is thought to relay auditory information to the inferior parietal lobule. Language inputs from the HLE may travel through this cortical pathway, such that the expanded superior temporal surface area could enable more neuronal connections projected to the inferior parietal lobule, leading to cortical thickening at the endpoint. The current findings added to this literature by revealing a similar pattern of association between the HLE, anatomical differences in the temporal-parietal language system, and children's OL abilities.

Uniquely from the HLE, parental SES predicted anatomical differences in the bilateral medial temporal gyri and, in turn, children's OL abilities. In particular, differences were reported in the cortical thickness of the left medial temporal gyrus, as well as surface area of the right medial temporal gyrus. The medial temporal gyrus encompasses the hippocampus and underlie learning and memory processes, which are thought to be important for language development (Duff & Brown-Schmidt, 2012; Ullman, 2004). Past studies have provided evidence linking parental SES to the development of children's medial temporal and hippocampal system (Leonard et al., 2015; McDermott et al., 2019). Differences in the hippocampal volume and activity have further been shown to mediate the impact of parental SES on children's memory and vocabulary scores (Assari et al., 2020; Decker et al., 2020). Parental SES could interact with neuronal composition in the medial temporal gyrus in ways that yield differences in both cortical thickness and surface area, which could explain prior reports on the link between SES and the hippocampal gray matter volume (Decker et al., 2020). The current findings align with findings that parental SES relates to domain-general cognitive processes, such as learning and memory, which have consequences in multiple and even task-specific abilities, such as OL abilities.

### The home environment and children's EFs

Uniquely from the HLE, parental SES was related to anatomical differences in the cortical thickness of the right lateral prefrontal (centrally, the dorsal portion) and occipital-temporal cortices, as well as surface area of the bilateral superior parietal and right visual ventral cortices, which, in turn, predicted children's EFs. Extensive connections between the prefrontal cortex and other cortical regions have been considered as the core neural substrate of cognitive control and EFs (Panikratova et al., 2020). Studies have linked individual differences in EFs to a larger frontoparietal "multiple-demand" network, which includes the superior parietal lobule (Assem et al., 2020; Cole et al., 2013; Zanto & Gazzaley, 2013). The current findings are consistent with prior reports that showed the impact of parental SES on the prefrontal cortical anatomy (thickness and volume) and, in turn, children's EFs (Lawson et al., 2013; Shaked et al., 2018). The frontoparietal network has been analyzed extensively in relation to parental SES metrics (Ellwood-Lowe et al., 2021; Finn et al., 2017; Leonard et al., 2015). The current results also included the right ventral visual system, including the occipital-temporal area, that mediated the relation between parental SES and children's EFs. Previous reports have linked the connectivity between the frontoparietal network and visual system to visual attention processes, which was indexed by a flanker attention task (Chen et al., 2019). Parental SES could relate to how the frontoparietal and visual systems interact in ways that yield anatomical changes, such as surface area expansion, and accommodate children's EFs.

Anatomical differences in the left occipital-temporal cortex mediated the relative effects of the HLE and parental SES on children's EFs. The current findings are consistent with recent reports, which suggest that cognitive stimulation opportunities and parental SES could influence children's development of the ventral visual cortex (Rosen et al., 2018, 2019). Cognitive stimulation guided by parents is thought to drive children's ability to regulate visual attention, identify stimulus information, and form semantic representation (Rosen et al., 2018, 2019). The ventral visual system decodes bottom-up information and fine-tune EFs by sending inputs through a complex feedforward-feedback circuit with higher-order regions, such as the prefrontal cortex (Amso & Scerif, 2015; Gilbert & Li, 2013; Lynn & Amso, 2023). As previously mentioned, prior reports have linked the connectivity between the frontoparietal network and occipital-temporal cortex to visual attention processes (Chen et al., 2019). The current study found that parental SES was associated with both the frontoparietal network and occipital-temporal cortex and, in turn, EFs. These findings highlight the unique influence of parental SES on the neural correlates of children's EFs. At the same time, reading activities and print exposure in the HLE have been considered as a vehicle for visual attention (Neumann et al., 2015). It is possible that the HLE taps the neural projection from the occipital-temporal cortex to the frontoparietal network and, in turn, influence visual attention in a bottom-up manner. This would also be consistent with the hypothesis that early stages of reading development draw on general visual processes subserved by both the occipital-temporal regions (Booth et al., 2003; Church et al., 2008). Further work is needed to analyze whether and to what extent the HLE and parental SES may relate to children's WR skills and EFs through the lateralization of the occipital-temporal cortex.

## Additional considerations and future directions

Some limitations of the present study warrant mentioning and further investigations. Proximal variables in the HLE were estimated based on self-report questionnaires to parents and included items about shared book reading with children and children's independent print exposure. The current results are consistent with previous findings that used a questionnaire similarly to this and revealed the correlation between the HLE and the temporal-parietal language-supporting areas in children (Hutton et al., 2015, 2017). The current findings are also in line with another study that administered a questionnaire on book reading as well as direct teaching activities and showed the correlation between the HLE and children's bilateral occipital-temporal regions (Powers et al., 2016). Nevertheless, other studies have used nuanced naturalistic approaches to survey the language complexity in the home environment with the Language Environment Analysis (LENA) tool to directly capture parent-child conversational turns and family language use, and then linked these indices to brain metrics (Gilkerson, Richards, Warren, et al., 2017; Merz et al., 2020; Romeo et al., 2018). Future studies may want to consider systematic analyses of multiple measurements for the HLE and their associations with neurocognitive differences in children.

Parental SES was used a distal indicator of the home structural environment. Previous studies have shown that different SES components, such as parental level of educational attainment and household income-to-needs ratio, predict common as well as unique brain regions. These different SES components could have differential impacts on the relation between the HLE and children's reading development (K. G. Noble et al., 2015). Therefore, future studies may consider assessing the relations between the HLE, parental SES, and children's neurocognitive systems with more comprehensive SES measures. Further, prior analyses have functional brain imaging and task contrasts to investigate the neural correlates of behavioral differences (WR skills, OL abilities, EFs, etc.). The current study referenced prior functional analyses to interpret anatomical brain differences using reverse inferences, which could include possible false positive findings. Combining multiple brain imaging modalities may provide in-depth insights on the functional implications of the extent to which the home environment influences children's brain development. Use of multiple modalities could reveal, for example, how the HLE and parental SES relate to differences in the anatomy of cortical regions and their underlying white-matter connectivity and functional circuitry (Tooley et al., 2021).

# CHAPTER 4

## Study 3: The home environment and neural correlates of reading

### Motivation

The aim for **Study 3** was to understand the extent to which neural systems impacted by the HLE and parental SES predict children's RC outcomes. Putting the previous two studies together, findings support the idea that there are largely distinct, with a modest overlapping, patterns of associations between the HLE and parental SES and different neurocognitive systems. The HLE and parental SES were commonly associated with anatomical differences in the brain occipital-temporal regions and, in turn, children's decoding skills. Uniquely from parental SES, the relation between the HLE and children's OL abilities was shown to be mediated by the temporal auditory association and inferior parietal regions. Uniquely from the HLE, the relation between parental SES and children's EFs was mediated by the prefrontal and superior parietal regions. Here, longitudinal analysis strategies were applied to further analyze whether these neural systems impacted by the HLE and parental SES ultimately predict differences in children's RC outcomes.

RC performance has been linked to neural systems implicated in WR skills and OL abilities, as well as EFs. Studies have shown that the occipital-temporal cortex within the visual ventral stream is involved in not only word-level WR skills, but also sentence- and passage-level RC abilities (Aboud et al., 2016; Cutting et al., 2006; Ozernov-Palchik et al., 2021; Saygin et al., 2016). Beyond the word level, RC also places a high demand on OL abilities, which have been shown to be supported by the temporal-parietal cortex (Cutting et al., 2006; Ferstl & von Cramon, 2001; Just et al., 1996; Walenski et al., 2019)., Further, the prefrontal-EF system appears to be recruited in RC, which is not altogether surprising because of its extensive connectivity with other regions in the brain, including those within occipital-temporal and temporal-parietal cortices (Aboud et al., 2016; H. Kim et al., 2022; Wang et al., 2020). These cortical areas implicated in these reading subprocesses—WR skills, OL abilities, and EFs—are candidate pathways through which the home environment could influence children's RC outcomes.

## Links between the home environment and neural correlates of reading

### The home environment, the occipital-temporal cortex, and reading

The HLE could influence children's reading outcomes through the occipital-temporal cortex implicated in reading skills (at both WR and RC levels). Through the HLE, children could be engaged in activities with print that promote familiarity with written words, sensitivity to spelling patterns, and awareness of grapheme-phoneme correspondence (Sénéchal, 2006; Sénéchal & LeFevre, 2002). The HLE has been shown to predict activity in the bilateral occipital-temporal regions while children were doing a phonological task in the scanner (Powers et al., 2016). The same study also linked the impact of the HLE to activity in the inferior frontal gyrus and superior temporal gyrus (Powers et al., 2016). Another study has shown that the HLE relates to activity in the inferior frontal gyrus during a visual word adaptation task (Girard et al., 2021). The left occipital-temporal gyrus is known to support WR skills, while the involvement of the right-hemisphere occipital-temporal homologue has been implicated to underlie neural compensatory and/or general visual processes in reading development (Booth et al., 2003; Church et al., 2008; Hoeft, Meyler, et al., 2007; Nugiel et al., 2019). The inferior frontal gyrus and superior temporal gyrus play a role phonological perception, as well as lexico-semantic functions, both of which have been implicated in WR and RC outcomes (Aboud et al., 2016; Joseph et al., 2001; Perdue et al., 2020; Turkeltaub et al., 2002). Analyses in all the aforementioned studies adjusted for parental SES, thus these findings are unique to the HLE and the occipital-temporal regions implicated in reading.

Parental SES has been linked to reading through the occipital-temporal regions. One study has shown that the association between children's phonological awareness and activity in the occipital-temporal cortex during a visual word recognition task varies by parental SES (K. G. Noble et al., 2006). In particular, children from lower parental SES backgrounds showed an interaction between phonological awareness and the occipital-temporal activity (K. G. Noble et al., 2006). It has also been found that children from lower parental SES backgrounds tend to leverage the right inferior longitudinal fasciculus tract to facilitate reading outcomes, whereas peers from higher parental SES show a reliance on the left hemisphere tract (Gullick et al., 2016). The inferior longitudinal fasciculus is a tract that runs along the inferior temporal and occipital-temporal cortices (Yeatman et al., 2013). One study has carefully controlled for the HLE, revealing that parental SES remained a unique predictor of the diffusion of the inferior longitudinal fasciculus and, in turn, reading outcomes (Ozernov-Palchik et al., 2019). It is possible that parental SES influences the visual processes subserved by the occipital-temporal regions in ways that facilitate children's reading development.

### The HLE, the temporal-parietal cortex, and reading

The HLE could impact children's reading outcomes through the temporal-parietal regions implicated in OL abilities. Meaning-focused activities, such as shared book reading with parents, have been shown to bolster children's oral comprehension abilities and, in turn, RC outcomes (Sénéchal, 2006; seneschal & LeFevre, 2002). Using story listening tasks in the scanner, studies have shown that the HLE predicts activity in the temporal-parietal cortex, including the superior temporal gyrus and inferior parietal lobule, as well as the inferior frontal gyrus and posterior cingulate cortex (Hutton et al., 2015, 2017). These temporal-parietal regions are thought—and have been shown—to interact in ways that enable complex language processing and discourse mentalizing functions that support OL and RC (Aboud et al., 2019; Jacoby & Fedorenko, 2020; Wilson et al., 2008).

Parental SES appears to impact parent-child language interactions and, in turn, brain regions implicated in children's OL abilities. One study has shown that taking turns in conversation mediate the impact of parental SES on activity in the inferior frontal gyrus during a story listening task, which in turn predicted out-of-scanner language abilities (Romeo et al., 2018). Another study has revealed that taking turns in conversation mediate the associations between parental SES, surface area of the superior temporal gyrus, and children's reading outcomes (Merz et al., 2020). Language interactions are especially abundant in the HLE and may explain the impact of parental SES on language-supporting brain regions. In other words, parental SES through its overlapping variance with the HLE could account for the differences in OL-supporting brain regions.

### Parental SES, the prefrontal cortex, and reading

The impact of parental SES on children's prefrontal-EF system could have a downstream influence on reading outcomes. Parental SES has been linked to children's performance on behavioral assessments of EFs (Hackman et al., 2015; Lawson & Farah, 2017; Sarsour et al., 2011), functional brain activity during tasks that tax EFs (Kishiyama et al., 2009; Sheridan et al., 2012), and anatomical differences in the prefrontal cortex (Lawson et al., 2013; Shaked et al., 2018). Further, behavioral findings suggest that the impact of parental SES on children's EFs could relate to children's academic achievement, including reading and math (Z. T. Barnes et al., 2022; Blair & Razza, 2007; Hemmerechts et al., 2017). One imaging study showed that parental SES predicts activity in the prefrontal regions and superior parietal lobule during a complex working memory task, which in turn predicted children's math scores (Finn et al., 2017). In another study, parental SES was related to activity in the prefrontal cortex during an in-scanner phonological task, and this association overlapped with language indices (vocabulary knowledge) and perceptual abilities (Conant et al., 2017). These studies suggest that it is possible that parental SES relates to children's RC outcomes through the prefrontal regions, a supposition which is consistent with findings from Study 1.

## Current study

The current study aimed to elucidate the extent to which anatomical brain differences in children explained by the HLE and parental SES predict their RC outcomes. In particular, the longitudinal nature of the current sample was leveraged to analyze the relations between the home factors, indices of brain anatomy, and RC levels that were measured concurrently (after first grade) and a year later (after second grade). The HLE, parental SES, and indices of brain anatomy were regressed against first grade RC level to observe initial effects on reading. Then, the home and anatomical brain variables were treated as predictors of RC attainment captured after second grade, while controlling for prior-year scores (i.e., auto-regressor). Such an approach allows the examination of the relative effects of HLE and SES on not only concurrent RC ability, but also on changes in children's RC abilities. The following specific hypotheses were tested:

- ***Hypothesis 1***. Controlling for parental SES, the HLE will predict anatomical differences in the occipital-temporal regions, which in turn will predict RC outcomes.
- ***Hypothesis 2***. Uniquely from parental SES, the HLE will relate to anatomical differences in the temporal-parietal regions, which in turn will predict RC outcomes.
- ***Hypothesis 3***. After accounting for the HLE, parental SES will be related to anatomical differences in the prefrontal regions, which in turn will predict RC outcomes.

# Methods

## Sample

Participants and data were drawn from the same cohort of subjects included in Studies 1 and 2 (**Chapters 2** and **3**). For descriptive statistics, please refer to **Tables 2.3**. and **3.1**. The same indices of the home environment (the HLE and parental SES) used in Studies 1 and 2 were used as primary variables of interest here. The current study also included children's performance on the same RC tasks from Study 1 that were collected after first and second grades. As in Study 2, analyses controlled for background information collected from parents (reading history) and children (age, biological sex, handedness, school information [Title 1 Status], and perceptual reasoning).

## Analyses

### *Preliminary analyses*

Preliminary analyses were conducted to determine descriptive information and pairwise correlations between the HLE and parental SES indices and children's RC outcomes.

### *Regional mediation analyses*

Regional findings from whole brain analyses in Study 2 were included in mediation analyses to evaluate the relations between indicators of the home environment (the HLE and parental SES), anatomical brain indices, and RC outcomes. For each anatomical index, mediation analyses were run to correlate with RC level assessed after first grade, and then to predict RC outcome measured after second grade while controlling for prior-year RC level. Average causal mediation (indirect) effects were estimated based on the associations between HLE or SES and brain indices, and then between brain indices and cognitive abilities. Significance levels were determined by a permutation approach implemented in the *mediate()* function. Findings were reported after performing correction for multiple comparisons using the Bonferroni approach at $p < 0.05$.

# Results

## Preliminary Findings

Descriptive statistics of children's performance on the RC subtests are as follows. For RC level assessed after first grade, scores on the *WJ* Passage Comprehension subtest had $M = 471.80$, $SD = 17.78$, and fell between 400 and 512, and scores on the *GMRT* Comprehension subtest had $M = 439.13$, $SD = 42.92$, and fell between 346 and 540. For RC attainment evaluated after second grade, scores on the *WJ* Passage Comprehension subtest had $M = 485.41$, $SD = 13.09$, and fell between 447 and 515, and scores on the *GMRT* Comprehension subtest had $M = 482.67$, $SD = 42.90$, and fell between 372 and 577.

Preliminary analyses were also conducted to examine the pairwise correlations between the HLE, parental SES, and children's RC outcomes (using composite scores). The HLE and parental SES measures were positively correlated ($r = 0.238$, $p < 0.05$). Further, the HLE measure was positively correlated with RC performance assessed after first grade ($r = 0.368$) and with RC outcomes after second grade ($r = 0.381$) (both $p$'s $< 0.05$). Parental SES was also positively correlated with RC performance assessed with first grade ($r = 0.358$) and with RC outcome after second grade ($r = 0.323$) (both $p$'s $< 0.05$).

For the pairwise correlational findings among other variables used in the current analyses, including indices of the home environment (the HLE and parental SES) and background information from parents (reading history) and children (age, biological sex, school information [Title 1 Status], and perceptual reasoning), please refer to. **Table 3.2**

Whole brain findings for the relations between the HLE, parental SES, and indices of brain anatomy (cortical thickness and surface) could be found in **Figures 3.1-2**.

## Home Environment Indicators, Regional Cortical Thickness, and Reading Outcomes

### ***The HLE predictions*** (**Figure 4.1** and **Table 4.1**).

#### First grade RC.

Controlling for parental SES, the relation between the HLE and RC performance measured after first grade was significantly mediated by the cortical thickness of the left posterior cingulate cortex ($b = 0.020$), as well as the right inferior parietal lobule and occipital-temporal cortex ($b$'s $= 0.022$ and $0.025$, respectively) (all $p$'s $< 0.05$).

**Second grade RC**.

Controlling for parental SES and prior-year RC level, the relation between the HLE and RC outcome measured after second grade was significantly mediated by the cortical thickness of the right temporal-parietal and occipital-temporal cortices ($b$'s = 0.019 and 0.018, respectively; both $p$'s $< 0.05$).

***Parental SES predictions*** (**Figure 4.2** and **Table 4.1**).

**First grade RC**

After controlling for HLE, no findings reached significance for the relations between parental SES, regional cortical thickness, and RC performance measured after first grade ($p > 0.05$).

**Second grade RC**.

After controlling for HLE, and prior-year RC level, the relation between parental SES and RC outcomes measured after second grade was significantly mediated by the cortical thickness of the right precentral gyrus ($b = 0.019$, $p < 0.05$).

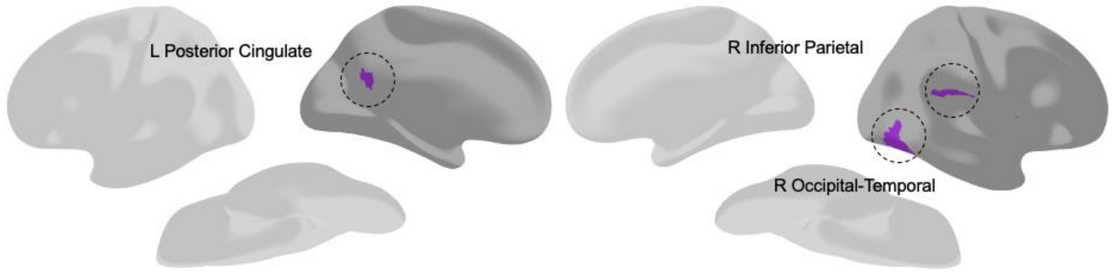
**Table 4.1**. Summary findings for regional cortical thickness and reading scores.

| **Contrast** | **Region** | ***b*** | ***CIs*** | ***%*** |
|---|---|---|---|---|
| **The HLE predictions** | | | | |
| → RC (1st grade) | L Posterior Cingulate Cortex | 0.020 | (0.003, 0.038) | 5% |
| | R Inferior Parietal Lobule | 0.022 | (0.011, 0.032) | 10% |
| | R Occipital-Temporal Cortex | 0.025 | (0.008, 0.043) | 13% |
| → RC (2nd grade) | R Temporal-Parietal Cortex | 0.019 | (0.010, 0.029) | 11% |
| | R Occipital-Temporal Cortex | 0.018 | (0.010, 0.025) | 17% |
| **Parental SES predictions** | | | | |
| → RC (1st grade) | - | | | |
| → RC (2nd grade) | R Precentral gyrus | 0.019 | (0.012, 0.027) | 23% |

*Note*. Indirect effects (*b*) were presented below with 95% confidence intervals (*CI*s) and the proportion of the total effect mediated (%). All indirect effects met $p < 0.05$.

**Figure 4.1**. The HLE, regional cortical thickness, and reading scores.

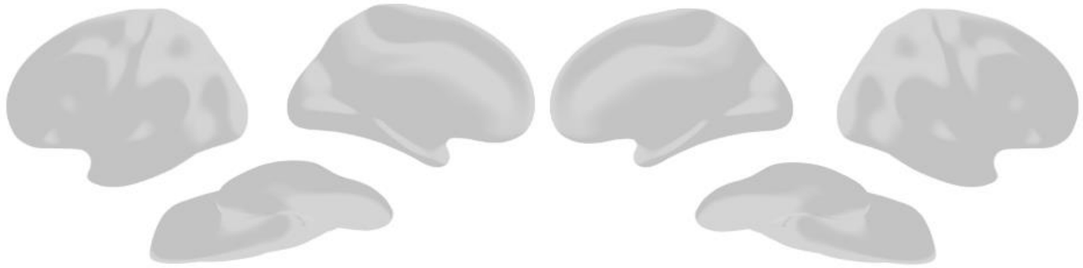
(a) First grade RC**.**



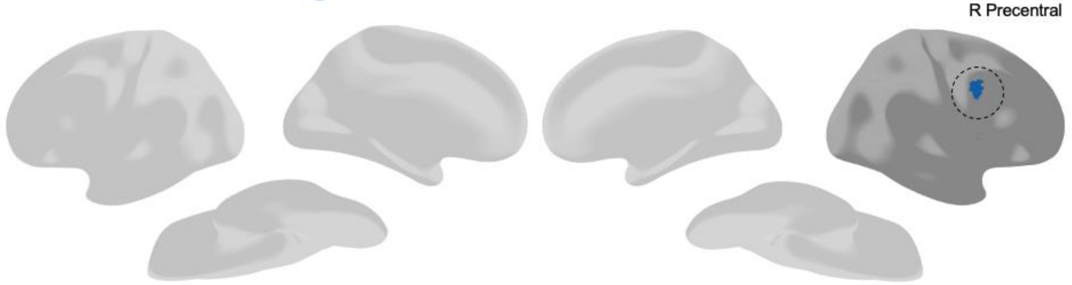
(b) Second grade RC.

**Figure 4.2**. Parental SES, regional cortical thickness, and reading scores.

(a) First grade RC**.**



(b) Second grade RC.



## Home Environment Indicators, Regional Surface Area, and Reading Outcomes

### *The HLE predictions* (**Figure 4.3** and **Table 4.2**).

#### **First grade RC**.

Controlling for parental SES, the relation between the HLE and RC performance measured after first grade were significantly mediated by the cortical thickness of the left auditory association cortex ($b = 0.035$), as well as the right inferior frontal gyrus and ventral visual cortex ($b$’s = 0.010 and 0.018, respectively) (all $p$’s < 0.05).

#### **Second grade RC**.

After controlling for parental SES and prior-year RC level, the relation between the HLE and RC outcome measured after second grade was significantly mediated by the surface area of the bilateral auditory association cortices ($b$’s = 0.015 and 0.027, respectively), left inferior parietal lobule ($b = 0.023$), right lateral temporal cortex ($b = 0.028$), and right posterior cingulate cortex ($b = 0.025$) (all $p$‘s < 0.05).

### *Parental SES predictions* (**Figure 4.4** and **Table 4.2**).

#### **First grade RC**.

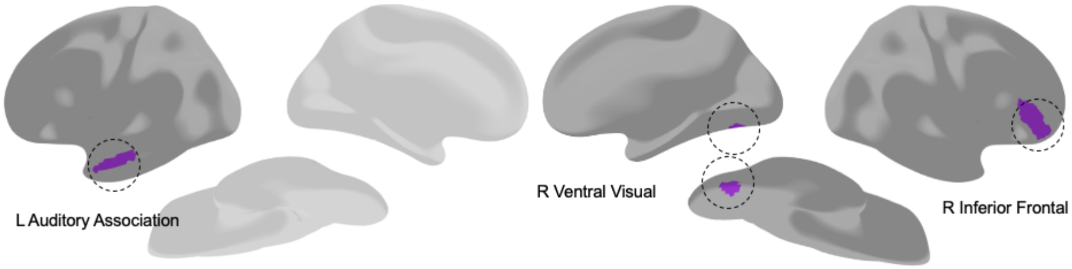
After controlling for the HLE, the relation between parental SES and RC performance measured after first grade was significantly mediated by the cortical thickness of the right ventral visual cortex ($b = 0.024$, $p < 0.05$).

#### **Second grade RC**.

After controlling for the HLE and prior-year RC level, the relation between parental SES and RC outcome measured after second grade was significantly mediated by the cortical thickness of the bilateral superior parietal lobules ($b$’s = 0.018 and 0.014, respectively) and right occipital-temporal cortex ($b = 0.019$) (all $p$’s < 0.05).

**Figure 4.3**. The HLE, regional surface area, and reading scores.

(c) First grade RC**.**



(d) Second grade RC.

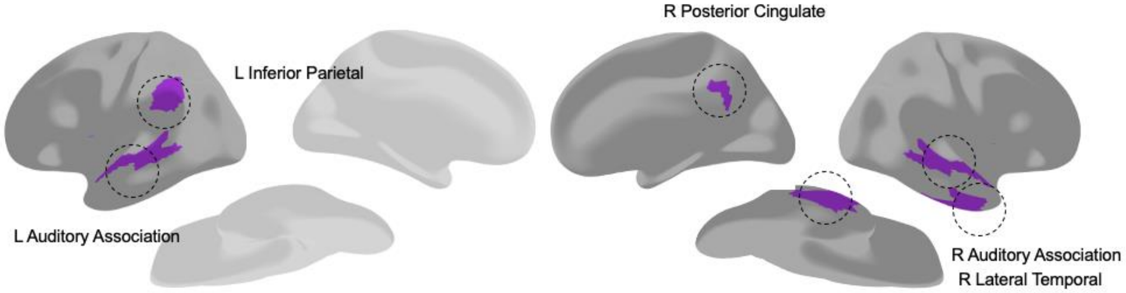
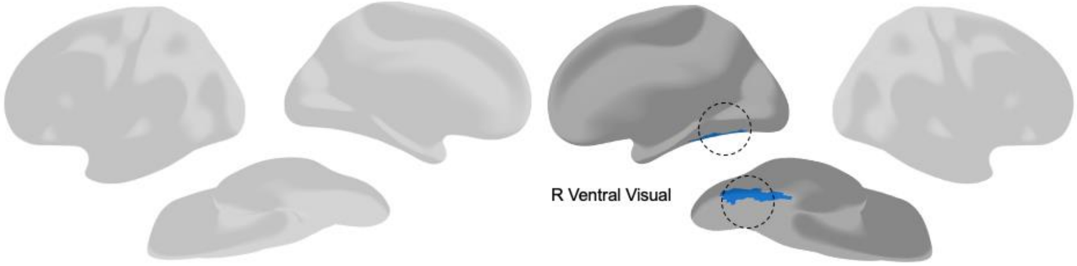


**Figure 4.4**. Parental SES, regional surface area, and reading scores.

(c) First grade RC**.**



(d) Second grade RC.

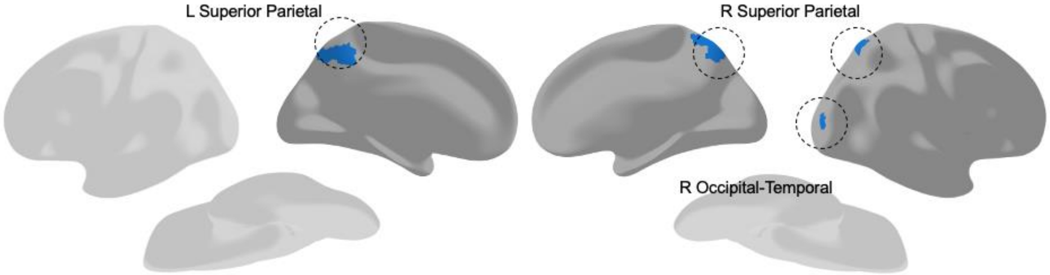
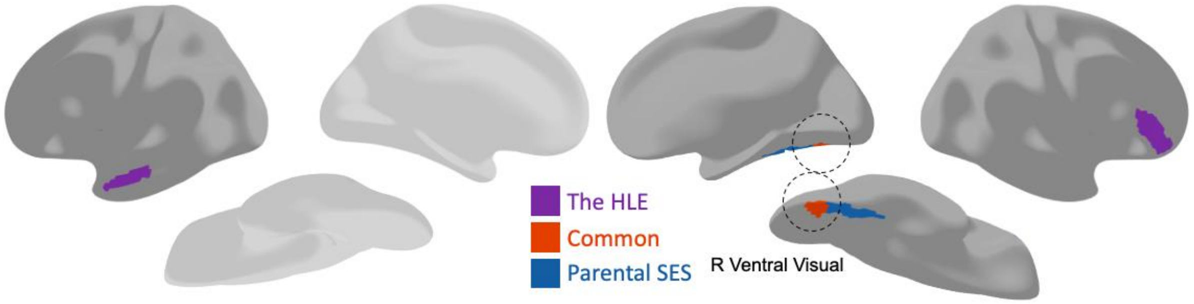


**Table 4.2**. Summary findings for regional surface area and reading scores.

| **Contrast** | **Region** | ***b*** | ***CIs*** | **%** |
|---|---|---|---|---|
| **The HLE predictions** | | | | |
| → RC (1st grade) | L Auditory Association Cortex | 0.035 | (0.003, 0.068) | 16% |
| | R Inferior Frontal Gyrus | 0.010 | (0.002, 0.019) | 4% |
| | R Ventral Visual Cortex [a] | 0.018 | (0.004, 0.032) | 7% |
| → RC (2nd grade) | L Auditory Association Cortex | 0.015 | (0.012, 0.017) | 10% |
| | L Inferior Parietal Lobule | 0.023 | (0.007, 0.038) | 16% |
| | R Lateral Temporal Cortex | 0.028 | (0.005, 0.051) | 17% |
| | R Auditory Association Cortex | 0.027 | (0.016, 0.038) | 29% |
| | R Posterior Cingulate Cortex | 0.025 | (0.010, 0.041) | 13% |
| **Parental SES predictions** | | | | |
| → RC (1st grade) | R Ventral Visual Cortex [a] | 0.024 | (0.012, 0.036) | 7% |
| → RC (2nd grade) | L Superior Parietal Lobule | 0.018 | (0.012, 0.024) | 12% |
| | R Superior Parietal Lobule | 0.014 | (0.006, 0.021) | 10% |
| | R Occipital-Temporal Cortex | 0.019 | (0.004, 0.034) | 18% |

*Note*. Indirect effects (*b*) were presented below with 95% confidence intervals (*CI*s) and the proportion of the total effect mediated (%). All indirect effects met $p < 0.05$. [a] denoted common finding between the HLE and parental SES predictions.

**Figure 4.5**. Common findings between the HLE and parental SES, regional surface area, and reading scores that were collected after first grade.



## Discussion

The aim of **Study 3** was to investigate the extent to which the neural systems impacted by the HLE and parental SES predicted children's RC attainment. Findings revealed that indices of the HLE and parental SES were commonly associated with anatomical differences in the right ventral visual cortex (see **Figure 4.5**), which include occipital-temporal regions, and in turn predicted children's RC outcomes. Uniquely from parental SES, the HLE was related to the right inferior frontal gyrus, bilateral auditory association (superior temporal) regions, left lateral temporal cortex, bilateral inferior parietal lobules, and bilateral posterior cingulate cortices and, in turn, RC outcomes. Uniquely from the HLE, parental SES was associated with the right precentral gyrus and bilateral superior parietal lobules and, in turn, RC outcomes.

### The home environment, the occipital-temporal regions, and reading

The HLE and parental SES were shown to commonly associate with differences in the surface area of the right ventral visual cortex and, in turn, first-grade RC outcomes. The left-lateralized occipital-temporal region within the ventral visual cortex plays a known role in rapid visual WR (Kravitz et al., 2013; McCandliss et al., 2003), whereas the involvement of the right-hemisphere homologue in reading is thought to engender either neural compensatory mechanism or general visual processes relevant in reading development (Booth et al., 2003; Church et al., 2008; Hoeft, Meyler, et al., 2007; Nugiel et al., 2019). One study has linked parental SES to children's phonological awareness and activity in the left occipital-temporal cortex during a visual recognition task (K. G. Noble et al., 2006). Another study has reported that children from lower- versus higher-SES backgrounds appear to rely on the right versus left inferior longitudinal fasciculus tracts to support WR outcomes (Gullick et al., 2016). Moreover, a portion of the right ventral visual cortex was found to remain uniquely associated with parental SES, even after controlling for the HLE, in predicting first-grade RC. This finding highlights the multifaceted role of parental SES in children's visual systems and reading development, aside from the contribution from the HLE. At the same time, the relative contributions of parental SES and the HLE in children's RC outcomes are in line with previous reports highlight the relative impacts of SES and cognitive enrichment on children's ventral visual system and, in turn, academic achievement (Rosen et al., 2019).

Uniquely from parental SES, the HLE was associated with cortical thickness of the right occipital-temporal regions and, in turn, children's RC outcomes assessed after first and second grades. These findings are consistent with a prior study, which showed that the HLE predicted activity in the bilateral occipital-temporal regions during a phonological awareness task (Powers et al., 2016). As aforementioned, while the interpretations are mixed, reports have posited the involvement of the right occipital-temporal cortex as a neural compensatory mechanism for WR skills (Hoeft, Meyler, et al., 2007; Nugiel et al., 2019), and/or a recruitment of general visual processes to accommodate the early stages of reading development (Booth et al., 2003; Church et al., 2008). Children who struggle with reading have been shown to draw on neural resources from the right-hemisphere homologues of the classical reading-supporting regions, including the inferior frontal gyrus and occipital-temporal cortex (Farris et al., 2011; Hoeft, Meyler, et al., 2007). Other studies have suggested that reading skills in early literacy acquisition may rely on visual processes from both left and right occipital-temporal cortices, which eventually become left-lateralized as children's WR skills improve (Booth et al., 2003; Church et al., 2008). The current findings suggest that the HLE could play a unique role through the right occipital-temporal regions to buffer reading difficulties and/or facilitate reading growth.

Uniquely from parental SES, the HLE was associated with surface area of the left auditory association cortex and right inferior frontal gyrus and, in turn, RC outcomes. These findings are consistent with a prior functional study that showed the association between the HLE and activity in the left inferior frontal and right superior temporal gyri, in addition to the bilateral occipital-temporal cortices, during a phonological processing task in the scanner (Powers et al., 2016). One anatomical imaging has shown that controlling for parental SES, parent-child conversational turns relate to the surface area of the superior temporal gyrus and, in turn, children's reading outcomes (Merz et al., 2020). The superior temporal gyrus is situated within the auditory association cortex and has an important role in auditory perception and phonological awareness (Cohen et al., 2004; Mesgarani et al., 2014). In the current study, the HLE was related to RC outcomes measured after first and second grades through the left auditory association cortex, suggesting that this area could mediate a longitudinal impact of the HLE on children's reading development. Another study reported that the HLE was associated with children's vocabulary knowledge and, in turn, activity in the inferior frontal gyrus during a visual word adaptation task (Girard et al., 2021). The inferior frontal gyrus appears to be involved in various lexico-semantic functions to process spoken and written language stimuli (Joseph et al., 2001; Turkeltaub et al., 2002). Though, the current study detected differences in the right-hemisphere inferior frontal gyrus, which is thought to implement a compensatory mechanism in reading (Aboud et al., 2018; Farris et al., 2011; Hoeft et al., 2011). Taken together, these findings suggest that the HLE taps the core and supporting brain regions implicated in word-level processes to facilitate children's RC outcomes.

### The HLE, the brain extended language network, and reading

Uniquely from parental SES, the HLE predicted RC outcomes through cortical thickness of the right inferior parietal lobule and temporal-parietal junction; surface area of the right lateral temporal cortex and left inferior parietal lobule; and cortical thickness and surface area of the left and right posterior cingulate cortices, respectively. These findings are consistent with previous studies that revealed that the HLE predicted activity in the temporal-parietal and posterior cingulate regions during story listening tasks (Hutton et al., 2015, 2017). The left inferior parietal lobule is thought to support phonological aspect of word processing, as well as the integration of word forms with their semantic representations (Hartwigsen et al., 2010; Stoeckel et al., 2009). Previous studies have reported that the inferior parietal lobule underlies efficient phonological decoding and automated orthographic recognition in mature reading (Houston et al., 2014; Phan et al., 2021). These temporal language areas are implicated in a range of semantic and OL functions at both the word and text levels, including sematic memory and control, syntactic parsing, and meaning associations across stimulus modalities (Ferstl et al., 2008; C. J. Price, 2012). The posterior cingulate cortex is thought to carry out mentalizing and contextualization functions that facilitate discourse and RC processes (Jacoby & Fedorenko, 2020; Maguire et al., 1999; Swett et al., 2013). The present results, showing that RC is linked to the lateral temporal cortex, temporal-parietal junction, inferior parietal lobule, and posterior cingulate cortex, suggest that the HLE has an impact on children's RC outcomes through the extended language neural network.

### Parental SES, the brain executive system, and reading

Uniquely from the HLE, parental SES was shown to predict cortical thickness of the right precentral gyrus, and surface area of the bilateral superior parietal lobules, and in turn children's second-grade RC outcomes. The precentral gyrus and superior parietal lobules fall within the frontoparietal "multiple-demand" network, which has been linked to individual differences in EFs

(Assem et al., 2020; Cole et al., 2013). Prior studies have reported that activity and anatomical differences in the frontoparietal network account for the extent to which parental SES relates to children's academic achievement (Finn et al., 2017; Rosen et al., 2018). One study identified the precentral gyrus, among other posterior lateral prefrontal regions, as an area that showed overlapping activity during reading, math, and EF tasks, suggesting that this is an EF area that also overlaps with executive processes needed for reading and math (Wang et al., 2020). Reading tasks have also been shown to evoke activity in the superior parietal lobule, potentially due to reliance on the working memory system to store and process text contents (Cutting et al., 2006). Together the present findings suggest that the impact of parental SES on children's frontoparietal network could have a downstream influence on reading-related processes. Moreover, the current study showed that the impact of parental SES on the frontoparietal regions related to children's second-grade RC outcomes after controlling for prior-year scores. Reports have suggested that RC performance in later grades places increasing demands on children's EFs, such as when reading expository or nonfictional texts (Aboud et al., 2019; Peng et al., 2018). Parental SES could positively relate to the neural frontoparietal resources that could be leveraged during RC tasks in later grades.

## Additional considerations and future directions

Some limitations of the present study warrant mentioning and suggest that further investigations are needed. Anatomical brain imaging was used to analyze the relations between the HLE, parental SES, and neural correlates of children's RC outcomes. Studies examining the neurobiological architecture of reading have been largely conducted with functional brain imaging; functional approaches are advantageous as they allow for task designs and cognitive subtraction analyses that can pinpoint specific aspects of the neural corelates of reading (Cutting et al., 2006; Jacoby & Fedorenko, 2020; Ozernov-Palchik et al., 2021). Some reports have adopted nuanced strategies to model interactions among brain systems, such as connectivity analyses, thus revealing insights into linkages between language and executive networks during reading (Aboud et al., 2016; H. Kim et al., 2022). The neural correlates of reading have largely been examined using task-based functional brain imaging. Findings from this line of research in part lend support for interpreting the current results on anatomical brain differences – that is, using reverse inference. A few studies on the HLE have used functional brain imaging to analyze influences of the home environment on children’s neural activity differences during reading-related tasks (Girard et al., 2021; Hutton et al., 2015, 2017; Powers et al., 2016). Evidence of the relations of parental SES on children’s neurocognitive systems comes from other brain imaging modalities as well. Findings have been reported for other imaging modalities, including anatomical imaging to assess the cortical morphology, functional imaging at rest, and diffusion imaging to visualize white matter tracts connecting cortical regions (Finn et al., 2017; Lawson et al., 2013; Ursache & Noble, 2016). Future studies should consider systematically analyzing the extent to which the HLE and parental SES relate to the neurobiological underpinnings of children’s reading abilities with multimodal imaging strategies, which may provide a more complete picture of the influences of the HLE and parental SES on neural systems, especially where overlaps were found, even when controlling for the HLE versus parental SES.

# CHAPTER 5

## Discussion: The home environment and neurocognitive systems in reading

### Motivation

Learning how to read is an important milestone in childhood, yet the many skills and processes involved can make reading difficult to master. Encouragingly, previous studies have revealed that there are factors in the home environment, including the HLE and parental SES, that can contribute positively to children's literacy readiness and reading outcomes (Kieffer, 2012; Sénéchal, 2006). The current thesis built on this wealth of research and attempted to delineate the extent to which, and how, the HLE versus parental SES related to the neurocognitive correlates of reading and RC itself. Across the three studies, these associations were examined using three specific hypotheses posed in the introduction, which posited involvement of 1) the WR skills and underlying occipital-temporal cortex, 2) complex OL abilities and the temporal-parietal network, and 3) the domain-general prefrontal-EF system in RC outcomes. Below is a summary of the findings across the three studies, which shed light on the patterns of associations between the HLE and parental SES and these three underlying neurocognitive factors in children's RC development.

### Links between the home environment and neurocognitive correlates of reading

Because the HLE and parental SES metrics capture different factors and variables in the home environment, it follows that the neurocognitive mechanisms underlying their influences on children's RC outcomes should differ. The HLE includes literacy activities and reading behaviors that enable children to have proximal interactions with processes implicated in WR skills and OL abilities (Sénéchal, 2006; Sénéchal & LeFevre, 2002). Parental SES is a distal indicator of the structural conditions and resources in the home, and appears to have a broad impact on multiple neurocognitive systems in children, including cortical regions linked to WR skills, as well as OL and EF abilities (Antonoplis, 2022; K. G. Noble et al., 2005, 2006, 2015). Using path modeling, findings in **Study 1** (Chapter 2) suggested that while the HLE was related to children's RC outcomes indirectly through WR skills and OL abilities, parental SES was related to RC outcomes indirectly through the impact of EFs on WR skills and OL abilities. Additionally, parental SES had a direct impact on WR skills, which was unexpected. **Study 2** (Chapter 3) and **Study 3** (Chapter 4) demarcated that the patterns of associations between the HLE, parental SES, and the neurocognitive systems implicated in reading. The HLE and parental SES were shown to be commonly associated with anatomical differences in the right occipital-temporal cortex in the ventral visual cortex, which in turn predicted children's WR skills and RC outcomes. Uniquely from parental SES, the HLE was related to differences in the parietal-temporal cortex and, in turn, children's OL abilities and RC outcomes. Uniquely from the HLE, parental SES was related to differences in the prefrontal and superior parietal cortices and, in turn, children's EFs and RC outcomes.

### The home environment, the brain reading network, and reading

The HLE was associated with children's RC outcomes through WR skills and right occipital-temporal cortex. Study 1 showed that after controlling for parental SES, the HLE was related to children's WR skills measured after first grade and, in turn, RC outcomes assessed a year later. Studies 2 and 3 showed that the HLE was associated with anatomical differences in the right occipital-temporal cortex and, in turn, predicted children's WR skills and RC outcomes. Sénéchal's *Home Literacy Model* hypothesizes that print-focused activities and reading behaviors in the HLE offer children direct exposure to the word-form and speech-sound aspects of language (Sénéchal, 2006; Sénéchal & LeFevre, 2002). One study has shown that the HLE predicts activity in the bilateral occipital-temporal cortices during a phonological processing task (Powers et al., 2016). The left occipital-temporal cortex serves as an important region in rapid visual word recognition, integrating inputs from the visual and auditory systems (Dehaene et al., 2010; McCandliss et al., 2003). As such, recruitment of the left occipital-temporal cortex has been repeatedly shown to be important in both word-level decoding and passage-level reading processes (Aboud et al., 2016; Ozernov-Palchik et al., 2021). Although to a lesser extent, studies have linked the right occipital-temporal cortex to reading (Church et al., 2008; Hoeft, Ueno, et al., 2007; Nugiel et al., 2019). Some findings showed that compared to their peers with typical reading trajectories, children with reading difficulties tend to exhibit differences in the right-hemisphere homologues of the left reading-supporting regions, including the inferior frontal gyrus and occipital-temporal cortex (Aboud et al., 2018; Farris et al., 2011; Hoeft, Meyler, et al., 2007; Nugiel et al., 2019).

These findings were interpreted as the right occipital-temporal cortex could provide a neural compensatory mechanism in the face of reading challenges (Hoeft, Meyler, et al., 2007). On the other hand, it is possible that the HLE could relate to right occipital-temporal cortex and, in turn, support reading processes in early stages of reading. Using functional reading and rhyming tasks, other studies suggest that the right occipital-temporal cortex could underlie general visual processes needed when acquiring reading skills (Booth et al., 2003; Church et al., 2008). The occipital-temporal cortex was hypothesized to then become left-lateralized to support rapid visual word recognition as children advance to later stages of reading development and beyond (Booth et al., 2003; Centanni et al., 2017). The HLE could interact with visual processes subserved by the occipital-temporal regions in ways that influence children's reading development.

Even after controlling for the HLE, parental SES remained a significant predictor of children's WR skills and RC outcomes through a common impact on the right occipital-temporal cortex. Study 1 showed that after controlling for the HLE, parental SES explained unique variance in children's WR skills, and in turn RC outcomes. Studies 2 and 3 showed that the HLE and parental SES were commonly associated with anatomical differences in the right occipital-temporal cortex and, in turn, predicted children's WR skills and RC outcomes. As previously mentioned, the involvement of the right occipital-temporal gyrus in reading has been thought to provide a neural compensatory mechanism and/or general visual resources for the early stages in reading development (Booth et al., 2003; Church et al., 2008; Hoeft, Meyler, et al., 2007; Nugiel et al., 2019). Prior studies have shown that children from lower- versus higher-SES backgrounds appear to rely on the right versus left inferior longitudinal fasciculus tract to facilitate reading skills (Gullick et al., 2016). The inferior longitudinal fasciculus is a white matter tract that runs along the inferior temporal and occipital-temporal cortices (Yeatman et al., 2013). Children from lower-SES backgrounds have been hypothesized to leverage visuospatial skills to support reading outcomes (Gullick et al., 2016). At the same time, the current findings are consistent with recent reports, which have suggested that parental SES and cognitive stimulation opportunities relate to differences in children's ventral visual regions and, in turn, academic achievement (Mackey et al., 2015; Rosen et al., 2018, 2019). The occipital-temporal regions lie within the ventral visual cortex, which receives inputs from multiple high-order cortical regions. Some theoretical accounts have implicated a role for the ventral visual cortex in visual attention through feedforward-feedback interactions with higher-order regions (Amso & Scerif, 2015; Gilbert & Li, 2013). Studies have shown that the connectivity between the occipital-temporal cortex and frontoparietal network predicts visual attention processes (Chen et al., 2019). As discussed below, parental SES also relates to anatomical differences in the frontoparietal network to influence children's EFs. It is possible that parental SES relates to the frontoparietal network that has a downstream influence on the occipital-temporal cortex and, in turn, children's reading outcomes.

Uniquely from parental SES, the HLE was related to children's reading outcomes through the inferior frontal gyrus. Studies 2 and 3 showed that anatomical differences in the right inferior frontal gyrus mediated the relations between the HLE and children's WR skills and RC outcomes. Past studies have reported that the HLE predicts activity in the left inferior frontal gyrus during a phonological awareness task (Powers et al., 2016), a visual word adaptation task (Girard et al., 2021), and a story listening task (Hutton et al., 2017). The inferior frontal gyrus has been implicated in a diverse set of lexico-semantic functions that are thought to enable processing of written and spoken language stimuli. Involvement of the right-hemisphere inferior gyrus is believed to serve a compensatory mechanism to promote efficient reading outcomes (Farris et al., 2011; Hoeft et al., 2011), potentially by leveraging the connections with regions implicated in language processes (Aboud et al., 2018). Indeed, a recent study showed that the HLE relates to left lateralization of the superior longitudinal fasciculus tract, a tract that connects the inferior frontal gyrus and inferior parietal lobule (Davison et al., 2023). These indices, in turn, predicted children's reading outcomes (Davison et al., 2023). It is possible that the HLE promotes the recruitment of compensatory neural mechanisms through the right inferior frontal gyrus to support language processes and in turn RC, which may be especially important to consider for those children facing reading difficulties.

### The HLE, the brain language system, and reading

Uniquely from parental SES, the HLE was associated with children's RC outcomes through OL abilities and the temporal-parietal cortex. Study 1 showed that after controlling for parental SES, the HLE was uniquely related to children's OL abilities, which in turn predicted RC outcomes. Studies 2 and 3 showed that the HLE was associated with the temporal auditory association cortex and inferior parietal lobule, and in turn children's OL and RC outcomes. In addition, the HLE was shown to predict differences in the lateral temporal cortex and posterior cingulate cortex and, in turn, children's RC outcomes. Sénéchal's *Home Literacy Model* hypothesizes that meaning-focused activities in the HLE, such as shared book reading with parents, benefit children's oral comprehension abilities (Sénéchal, 2006; Sénéchal & LeFevre, 2002). Previous behavioral studies using path modeling approaches have clearly shown that the HLE, uniquely from parental SES, contributes to children's language and reading development (Hamilton et al., 2016; Inoue et al., 2018a). Similarly, brain imaging analyses have shown that the HLE predicts activity in the extended language network during story listening tasks (Hutton et al., 2015, 2017). In these studies, findings linked to the HLE included the lateral temporal cortex, middle-superior temporal regions within the auditory association cortex, and inferior parietal lobule, as well as the posterior cingulate cortex (Hutton et al., 2015, 2017). The superior temporal gyrus is important for facilitating word form detection and segmentation of phonological cues (Cohen et al., 2004; Mesgarani et al., 2014). Studies have shown that this area of the brain relays auditory information to higher-order language hubs like the lateral temporal cortex and regions in the inferior particular lobule, including the angular gyrus, to implement complex language functions (Ferstl et al., 2008; Friederici, 2011; Wilson et al., 2008). Involvement of the posterior cingulate cortex has also been implicated in complex language processes, particularly those attributable to discourse processing and mentalizing functions (Maguire et al., 1999). Together, the present findings suggest that the HLE makes an important contribution to various OL processes subserved by the temporal-parietal cortex.

### Parental SES, the brain executive system, and reading

Uniquely from the HLE, parental SES was associated with children's RC outcomes through EFs and the prefrontal and superior parietal regions, both of which belong to the frontoparietal network that supports EF processes (Assem et al., 2020; Cole et al., 2012, 2013). Study 1 showed that after controlling for the HLE, parental SES was uniquely associated with children's EFs, which in turn was indirectly related to RC outcomes. Studies 2 and 3 showed that parental SES was associated with anatomical indices of the prefrontal gyrus and superior parietal lobule, which in turn predicted children's EFs and RC outcomes. Parental SES is a distal factor thought to permeate various factors in the home environment and influence multiple neurocognitive domains in children's development (Antonoplis, 2022; Duncan & Magnuson, 2012, 2003). Given the prolonged development of the prefrontal cortex, parental SES has been posited to have a profound impact on the prefrontal-executive system in children (Kolb et al., 2012; Tooley et al., 2021). Previous studies have linked parental SES to various metrics of children's prefrontal-executive system, including behavioral assessments of EFs, activity in the prefrontal cortex during EF tasks, and cortical morphology of the prefrontal cortex (Hackman et al., 2015; Last et al., 2018; Lawson et al., 2013; Shaked et al., 2018; Sheridan et al., 2012). The current findings are consistent with those that have shown that parental SES relates to differences in not only the prefrontal cortex, but also the superior parietal lobule, which in turn predict children's academic achievement (Finn et al., 2017; Rosen et al., 2018). The prefrontal and superior parietal regions fall within the frontoparietal network, which has extensive connections with other cortical regions and supports a range of domain-general functions (Assem et al., 2020; Cole et al., 2012, 2013). Some studies have linked the connectivity between the frontoparietal network and ventral visual cortex to visual attention processes, versus the connectivity between the superior temporal auditory regions and ventral visual cortex to reading and language abilities (Chen et al., 2019; Vogel et al., 2012). The current findings suggest that the impact of parental SES on the frontoparietal network could have a downstream on children's reading development and the underlying occipital-temporal regions.

## Additional considerations and future directions

There are other factors closely related to the HLE and parental SES that have been shown to benefit children's reading development, including literacy resources, language complexity, and scaffolding practices. Literacy resources, most often operationalized by the number of books available to children at home, could be a putative facilitator of shared reading (Sénéchal, 2006). Literacy resources have been used to describe the meaning-related aspect of the HLE and appear to explain unique variance in children's reading (Inoue et al., 2018a; Sénéchal, 2006). Though, some reports have questioned the mechanism underlying the impact of literacy resources on children's reading development (Georgiou et al., 2021; Zuilkowski et al., 2019). In addition to literacy resources, language complexity has previously been analyzed using naturalistic approaches, such as with the Language Environment Analysis Tool, which produces metrics for parent-child conversational turns and family language use (Gilkerson, Richards, Warren, et al., 2017). Some studies have applied this naturalistic approach to measure how language complexity unfolds over the course of a shared book reading experience between parent and child (Gilkerson, Richards, & Topping, 2017). In doing so, reports have revealed various scaffolding practices that could benefit children's comprehension of the book contents, such as through questioning and making inferences (Mol et al., 2008; Reese & Cox, 1999). Scaffolding practices in general have been linked to parental SES and children's EFs (Devine et al., 2016). Moreover, the relative impacts of factors in the home environment may change in accordance to the child's developmental reading stage. Children learning to read have been shown to benefit from guidance and scaffolding structured by parents and caregivers (Sénéchal, 2006). Studies have also shown that during the reading to learn phase, children's progress appears to benefit from independent print exposure and literacy activities (Georgiou et al., 2021). Future studies may want to consider examine the relative impacts of home environment indices on children's reading progress and neural correlates across different developmental timepoints.

Children's reading development is a product of the complex interactions between the environment, individual differences, and their underlying genetics. The *Mutualism Hypothesis* speculates that learning experiences and sociocultural opportunities associated with parental SES influence the developmental trajectories of domain-specific academic skills and domain-general cognitive abilities (Peng & Kievit, 2020). Children from higher-SES backgrounds tend to have more abundant opportunities for positive learning experiences, but many of these opportunities are thought to be limited or scarce among lower-SES contexts. Lower-SES contexts have also been linked to various adverse conditions, such as stress, psychoemotional deprivation, food scarcity, and limited access to different resources, which have been shown to negatively associate with children's neurocognitive development (e.g., Ellwood-Lowe et al., 2022; McNeilly et al., 2021). Additional factors linked to childhood and household-level SES include neighborhood and school SES and resources, which have previously been related to children's reading outcomes. For instance, school quality has been suggested to mediate the impact of higher parental SES advancement or lower childhood SES circumstances on children's reading trajectories (Kieffer, 2012). In turn, children with advantages linked to higher-SES circumstances and relatively stronger cognitive-academic abilities in early development appear to continue to benefit from such foundation. That said, sustained high-quality schooling and home cognitive environment could offset the spiraling effects of lower SES circumstances on children's academic achievement (Kieffer, 2012). While discussions of the current findings have focused on the experiential correlates of the home influences on neurocognitive development, the interaction between environment, genetics, and individual differences cannot be ruled outed. Past studies have shown that each additional year of education impacts parents' neurocognitive differences and behaviors, which could in turn have genetic influences on children's reading development (Ritchie & Tucker-Drob, 2018; van Bergen et al., 2017; Wertz et al., 2020).

The current findings are limited from making causal inferences about the relative impacts of home environment variables on children's reading development. The present studies are correlational in nature, thus only able to probe relations between home environment indices, neurocognitive differences, and children's reading outcomes. Intervention and time-sensitive designs would be suitable for being able to draw causal inferences regarding their associations. Interventions have been designed to enrich the HLE, such as teaching dialogic reading strategies to parents (Dowdall et al., 2020; Lonigan & Whitehurst, 1998), or summer book reading programs for students who have developed sufficient reading skills (J. S. Kim, 2007; J. S. Kim & White, 2008). One study was designed to study whether increases in maternal education are associated with gains in children's cognitive development (Magnuson et al., 2009). The study found that, among mothers with initially low levels of education, increases in maternal education to gains in not only aspects of children's home environment (e.g., maternal responsiveness and the provision of learning opportunities), but also children's OL abilities (Magnuson et al., 2009). Examples of interventions that cover both the HLE and parental SES-related differences are summer scaffolded book reading and book distribution programs for children from low-income families (especially for students in secondary and upper education levels, as advanced classes tend to place a high demand on language comprehension and background knowledge) (de Bondt et al., 2020; J. S. Kim & Quinn, 2013), as well as those that work with parents from low-SES backgrounds to develop cognitive strategies and even shift their mindset to scaffold their children's development (List et al., 2021).

## Conclusion

Learning how to read is an important milestone in middle childhood and has a lasting impact across the lifespan. The various skills and cognitive processes involved can make it difficult for many children to master reading. Parents play an important role in promoting their child's literacy readiness and reading achievement by engaging in reading activities together at home. This thesis demonstrated that while the influence of reading activities on children's reading outcomes seems to be directly driven by language development, childhood socioeconomic circumstances are indirectly linked to outcomes through executive functions. Investment in children's cognitive development could contribute positively to their future vocational pursuits, health, and well-being. At same time, investment in parents also yields a wide array of benefits, some of which could facilitate children’s reading development. We hope that the current findings will motivate further scientific research and inspire community and policymaking efforts to identify and apply ways and tools to elevate the lives and well-being of our families and children.

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