6-29-2024

Examining the Role of Language in Inhibitory Control Development Within the Context of Early Poverty

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by
Rita Lynn Taylor

A dissertation presented to
Washington University in St. Louis
in partial fulfillment of the
requirements for the degree
of Doctor of Philosophy

August 2024
St. Louis, Missouri

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Acknowledgments

Rita would like to acknowledge the generous support from the National Science Foundation Graduate Research Fellowships Program (grant numbers: DGE-213989; DGE-1745038).

We would like to offer special thanks to the families and research faculty, staff, and coordinators for their commitment to and diligent work on the ABCD Study.

Rita would like to dedicate this work to her family and community.

Rita Lynn Taylor

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ABSTRACT OF THE DISSERTATION

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Dr. Deanna M. Barch, Chair

Inhibitory control (IC) is a component of executive function that has been shown to be important for tasks which require self-regulation such as future-planning, decision-making, and prosocial interpersonal interactions. Some Vygotskian researchers have proposed that language ability in early life allows for improved IC and subsequent self-regulation via the internalization of rule systems. While some studies have demonstrated evidence for this internalization, no studies to date have examined impacts of language on inhibitory control performance amongst individuals from financially under resourced backgrounds. The current study aimed to determine whether and/or how childhood financial deprivation altered performance on IC tasks across time, and whether language ability explained the relation between childhood socioeconomic status and subsequent IC performance. The sample consisted of 11,876 participants from the Adolescent Brain Cognitive Development (ABCD) Study. Multilevel models were computed to estimate intercepts and slopes of language and IC outcomes across timepoints. Results revealed that increased financial deprivation at baseline predicted reduced performance on a language task and less improvement on language tasks across time. Increased financial deprivation was associated

with similarly lower performance on IC tasks and less improvement across time. Further, lower performance on language tasks predicted worse performance on IC tasks and less improvement across time. Follow-up mediation analyses revealed evidence for a partial mediation of language, where the relationship between baseline SES and subsequent IC performance was partially explained by intermediary performance on a language task. The findings of this study provide increased evidence to support Vygotsky's Sociocultural Theory of Development and highlight the importance of early language intervention particularly in environments which are financially under-resourced.

1. SPECIFIC AIMS

In the United States, children constitute a striking number of the nation's poor population (Children's Defense Fund, 2020). In 2022, over 16 percent of children lived in poverty, a statistic notably higher than that of the overall national poverty rate of 12.6 percent (U.S Census Bureau, 2022). In addition, disproportionately higher rates of poverty are observed in younger children as well as in children of color (Children's Defense Fund, 2020). Disproportionately high rates of poverty in children are especially concerning, as research has consistently demonstrated that early life poverty is associated with a host of unfavorable short- and long-term outcomes such as lower academic/occupational achievement, increased risk for neurodevelopmental disorders, substance abuse, behavioral problems, and depression (Blair & Raver, 2012; Nusslock & Miller, 2016).

One such outcome that has been repeatedly associated with early life poverty is reduced inhibitory control (Brown et al., 2013; Evans & Kim, 2013; Moilanen et al., 2010; Noble et al., 2015; Schmitt et al., 2015). Inhibitory control (IC) is a component of executive function (EF) that allows for the suppression of prepotent (dominant or automatic) responses (Barkley, 2001; Best & Miller, 2010; Munakata et al., 2011). IC is crucial in the implementation of goal-directed behaviors and future planning.

One mechanism that has been explored to explain the relationship between early life poverty and IC deficits is language. Increased language ability and word use in the home have been found to be strongly associated with both lower SES and reduced IC performance (Hughes & Ensor, 2011; Noble, McCandliss, & Farah, 2007). It is also important to note that increasing complexity of language ability coincides with marked increases in IC maturation (Gagne & Saudino, 2016). Some researchers have theorized that language enables greater internalization of previously externally controlled executive processes such as IC (McLeod, 2020; Vygotsky &

Luria, 1978; Zelazo & Frye, 1998). To date, this relationship has not been examined within the context of impoverished youth during early to middle childhood, a demographic which – as indicated by previous literature – is at particular risk of developing IC deficits (Allee-Herndon & Roberts, 2019; Chen et al., 2019; Evans & Kim, 2013; Finegood & Blair, 2017; Pacheco et al., 2018). **Thus, the overarching hypothesis of the current proposal is that lower SES in early to middle childhood will predict worse IC performance, which will be partially explained by language ability.** To address this overarching hypothesis, we will use data from the Adolescent Brain Cognitive Development (ABCD) Study spanning five timepoints (Baseline – Year 4 Followup). We will use these data to address the following aims:

Aim 1: Investigate the relations between SES and receptive vocabulary knowledge performance, including whether there are SES-associated changes in receptive vocabulary knowledge performance over time. Consistent findings within the reviewed literature have indicated strong correlations between SES and language ability, wherein increased poverty is associated with worse performance on a host of language tasks (Brooks-Gunn & Duncan, 1997; Merz et al., 2019; Miller et al., 2018; Perkins et al., 2013; Salmon et al., 2016). There is also evidence to suggest that increased early poverty is predictive of attenuated improvements in language tasks over time (Hoff, 2003). Based on this background, our hypotheses are that 1.1) lower SES will be associated with overall worse performance on a measure of receptive vocabulary knowledge and 1.2) lower SES at baseline will be predictive of less improvement on a measure of receptive vocabulary knowledge across timepoints. Linear mixed effects models were used to examine the relationships of SES to both intercepts and slopes of receptive vocabulary knowledge across timepoints.

Aim 2: Investigate the relations between SES and IC, including whether there are SES-associated changes in IC performance over time. As with Aim 1, relations between SES and IC have been well-established in the literature. Specifically, increased poverty is associated with worse performance on tasks that index IC (Raver et al., 2013; Roy et al., 2014; Schmitt et al., 2015). Further, research suggests that the early poverty could be stunting or hindering maturation of IC across time (Hardaway et al., 2012; Moilanen et al., 2010). The study's hypotheses are that 2.1) Lower SES at baseline will be associated with lower levels of IC across several modalities of assessment and 2.2) Lower SES will be predictive of less improvement across several modalities of IC assessment over time. Similarly to Aim 1, linear mixed effects models were used to examine the relationships of SES to both intercepts and slopes of IC modalities across timepoints.

Aim 3: Ascertain the relationship between receptive vocabulary knowledge task performance and different facets of IC cross-sectionally and examine the relation between receptive vocabulary knowledge and facets of IC across timepoints. Previous research has found relations between language ability and IC cross-sectionally, and there is some research and theory which suggests that language ability is predictive of IC development across time, though more research is much needed (Allee-Herndon & Roberts, 2019; Moilanen et al., 2010; Roy et al., 2014). The current study hypothesizes that 3.1) Poorer performance on a receptive vocabulary knowledge task will be associated with poorer performance on IC tasks cross sectionally and 3.2) poorer performance on a receptive vocabulary knowledge task will be predictive of less improvement on IC tasks over time. As with the previous aims, linear mixed effects models were used to examine the relationships of receptive vocabulary knowledge to both intercepts and slopes of IC across timepoints.

<u>Aim 4:</u> Determine whether language partially explains the relationship between SES and IC performance. Currently, there is a dearth of research that has examined the role of language ability as a potential mediator of poverty's relationship to IC performance. The current study's usage of multiple timepoints, higher power, and different modalities of IC measurement are much needed in order to more clearly determine whether language ability is a potential mediator. The current study hypothesizes that the relationship between lower SES at Time 1 and less improvement on IC across modalities at subsequent timepoints will be partially explained by performance on an intermediary (Time 2) receptive vocabulary knowledge task.

Potential Implications: While developmental researchers have more recently emphasized the importance of increased focus on cognitive development within impoverished environments, the literature is still largely lacking with regard to these populations. Providing increased clarity about the nature of the relationship between early to middle life poverty, language ability, and IC could potentially allow for more informed decisions to be made concerning early childhood intervention and could lead to the mitigation of negative outcomes commonly experienced within the context of childhood poverty.

2. BACKGROUND & HYPOTHESES

Interrelations between poverty, language, and IC have been investigated within the research literature. The current study aimed to expand this line of research, by systematically examining associations cross-sectionally and change longitudinally, and also by testing a theorized mechanism of language in the relation between early poverty and IC development.

<u>Aim 1:</u> Investigate the cross-sectional relations between SES and receptive vocabulary knowledge performance and examine whether there are SES-associated changes in receptive vocabulary knowledge performance over time.

A robust research literature supports the relationship between early life poverty and alterations in language development. Increased poverty is associated with reductions across several language domains such as vocabulary knowledge, syntax, and semantic understanding (Brooks-Gunn & Duncan, 1997; Merz et al., 2019; Miller et al., 2018; Perkins et al., 2013; Salmon et al., 2016). Several mechanisms have been proposed to explain the frequently observed relationship between increased poverty and worse performance on language measures. Some of these mechanisms include reduced environmental cognitive stimulation, increased home chaos, lower maternal education, and lower frequency/quality of speech (Demir & Küntay, 2014; Vernon-Feagans et al., 2012).

Lower resourced environments – such as those often characterized by poverty – are often less cognitively stimulating than more resourced environments, which can lead to comparative deficits across cognitive domains including language (Guo & Harris, 2000). Lurie et al. (2021) found that increased cognitive stimulation in the home was significantly associated with increased child expressive and receptive language ability. Several classic rodent studies have demonstrated that rodents raised in bare cages had decreased overall brain volume in comparison to rodents

raised in cages that included enrichment (toys, running wheels, etc.) (Bennet, 1964; Diamond et al., 1964).

Financial stress can also lead to general home disorganization, housing instability, or excessive noise/disruption. The research literature has come to describe these attributes as *home chaos*, and some of these aspects of home chaos are associated with alterations in language acquisition and development (Johnson et al., 2008; Petrill et al., 2007; Vernon-Feagans et al. 2012). Vernon-Feagans et al. (2012) demonstrated that home chaos – particularly disorganization – predicted lower receptive and expressive vocabulary performance in children at three years of age. Increased levels of noise in the home have been found to be negatively correlated with child reading ability (Johnson et al., 2008; Petrill et al., 2007).

Lower maternal education has been consistently associated with lower SES, and is even used as a proxy for poverty in some cases. The assumption is that individuals with lower educational attainment are more likely to have difficulty gaining access to certain resources or wages. Research has demonstrated that children of mothers who did not graduate from high school performed significantly worse on the Peabody Picture Vocabulary Test (PPVT) than children of mothers who graduated high school and children of mothers who graduated from college (Dollaghan et al., 1999). Several other studies have corroborated these findings (Justice et al., 2020; Patra et al., 2016; Zambrana et al., 2012). Furthermore, children of mothers with initial relatively low formal education, who then gained additional education, exhibited improvements in both expressive and receptive language domains (Magnuson et al., 2009).

Both quality and quantity of heard speech in the home has been found to be crucial in influencing language development in children (Farrant & Zubrick, 2011; Hart & Risley, 1995; Hoff, 2003; Rowe, 2012; Schwab & Lew-Williams, 2016). Several studies have demonstrated

differences in language use among lower SES and higher SES households (Hart & Risley, 1995; Hoff 2003; Rowe, 2012; Schwab & Lew-Williams, 2016). Hoff (2003) demonstrated that lower SES mothers generally used shorter "utterances" and less diverse word types when talking with children in comparison to higher SES mothers. Children of lower SES mothers subsequently demonstrated less improvement in vocabulary knowledge (Hoff, 2003). Increased number of books read-aloud between parents and children was associated with improved vocabulary knowledge (Farrant & Zubrick, 2011).

Neurally, poverty is associated with reduced left lateralization in the inferior frontal gyrus (IFG), a prefrontal region of the brain known to be crucial for language processing (Raizada et al., 2008). Further, reduced white matter integrity among children from more impoverished households has been found in tracts implicated in language processing like the uncinate fasciculus (UF), superior longitudinal fasciculus (SLF), and cingulum bundle (CB) (Dufford & Kim, 2017; Merz et al., 2019; Ursache & Noble, 2016). Correlates of poverty such as lower cognitive stimulation, home chaos, reduced quality/quantity of speech, and greater risk for exposure to toxins and nutritional deficits may be influencing alterations in language development via brain structures and connective tracts.

Taken together, the literature demonstrates that early poverty – as well as its correlates – is strongly associated with lower language ability across several domains. Further, based on the nature of the mechanisms relating poverty to reduced language ability, as well as the reviewed literature, it is likely that improvements in language performance across time will also be relatively reduced among children from lower SES households. After reviewing literature specific to each poverty correlate, it is evident that each likely contributes in explaining the relationship of lower SES to reduced language ability. The current study aimed to utilize more comprehensive measures

of poverty (e.g., income to needs, neighborhood deprivation, school measures of economic disadvantage) in order to examine the relation between SES and receptive vocabulary knowledge in the proposed sample both cross-sectionally and across time. These more comprehensive measures of SES allowed the researchers to accurately and concisely specify poverty – and likely correlates of poverty – in statistical analyses. Similarly, receptive vocabulary knowledge has been determined to be a good indicator of language ability in other domains including reading comprehension and semantic understanding (Pan et al., 2004). The hypotheses are:

Hypothesis 1.1: Lower SES will be associated with worse performance on a measure of receptive vocabulary knowledge (intercept modeled at baseline).

Hypothesis 1.2: Lower SES will be predictive of less improvement on a measure of receptive vocabulary knowledge over time (slope = change over time) from baseline to year 2 to year 4.

<u>Aim 2:</u> Investigate the cross-sectional relations between SES and IC and determine whether there are SES-associated changes in IC performance over time.

IC is a component of EF that allows for the successful suppression of prepotent, or automatic, responses. It is crucial for higher order reasoning such as goal-directed thoughts and behaviors, future planning, decision-making, and prosocial interactions. IC is considered to be one of the earliest emerging higher order cognitive functions and is an essential component of many other EF processes (Barkley, 2001; Best & Miller, 2010; Munakata et al., 2011). IC is supported by several brain regions, including the dorsal lateral prefrontal cortex (dlPFC), ventral lateral prefrontal cortex (vlPFC), motor cortex, and dorsal anterior cingulate cortex (dACC) (Durston et al., 2002; Garavan et al., 2006; Hwang et al., 2010; Luria, 1973; Milner, 1963; Miyake et al., 2000; Goldstein et al., 2007; Whittle et al., 2020). The motor cortex is primarily tasked with ensuring the

appropriate coordination of motor responses, the dACC is primarily implicated in error detection and conflict monitoring (or interference detection), and the vlPFC and dlPFC are tasked with executively orchestrating the appropriate responses (Ordaz et al., 2013). Working together, these regions allow for the successful inhibition of prepotent behaviors. Research has also suggested that the right hemisphere of the brain is more heavily implicated in IC (Chevrier et al., 2007; Garavan, Ross, & Stein, 1999).

Researchers have hypothesized that the foundations for IC begin to develop soon after birth, as demonstrated by experimental studies with infants that have used gaze and reaching tasks (Diamond, 1990; Holmboe et al., 2008, 2018). Maturation of IC is more easily observed in early childhood, particularly after language acquisition has occurred (Gagne & Saudino, 2016; Hughes & Ensor, 2007; Vallotton & Ayoub, 2011). Researchers have reported notable improvements in IC as early as 3½ years of age, or during the period of time when children are typically in preschool (Aksan & Kochanska, 2004; Diamond & Taylor, 1996; Kochanska et al., 2000). Carlson (2005) found that performance on a delay of gratification (DOG) task improved significantly between two and four years of age. Overall, the research suggests that children may achieve an IC milestone at approximately 3½ years of age wherein they are able to both verbalize understanding of IC tasks and better inhibit prepotent responses. IC continues to mature rapidly between the ages of 3½ years to six years. In particular, there are consistent differences in IC observed between individuals six years and older and individuals younger than six years. Research literature suggests that changes and/or maturation in IC after the ages of seven to nine years-old is more subtle, and thus, more difficult to empirically detect (Bruce et al., 2013; Casey et al., 1997; Johnstone et al., 2007). The research literature suggests that

computerized IC tasks are best for detecting experimental differences in IC after this age (Best & Miller, 2010).

IC during childhood is primarily indexed using behavioral, parent/teacher report, and neuroimaging (patterns of activation during fMRI tasks, analysis of volume/structure of IC-implicated brain regions, ERP during EEG tasks, etc.) methods. While these different modalities are thought to index the same general construct, it is commonly found that the correlation between them is low. For example, the correlation between subscales on the Behavioral Rating Inventory of Executive Function (BRIEF) and Conner's Continuous Performance Test (CPT-II) were low and insignificant among children diagnosed with ADHD (Bodnar et al., 2007). Similar discordance between parent/teacher report and behavioral/performance-based modalities have been found when measuring other components of EF as well. Toplak et al. (2013) suggested that parent/teacher report and behavioral modalities are likely indexing different levels of a particular cognitive process. Specifically, they indicated that more standardized behavioral measures are testing the limits of processing given an ideal highly structured environment while parent/teacher report measures are indexing how IC may be impacting the effectiveness of goal-setting and achievement (Toplak et al., 2013). They, along with other researchers have cautioned against using behavioral and parent/teacher-report measures of IC as corresponding or exchangeable (Biederman et al., 2008; Toplak et al., 2013).

Notable maturation of IC occurs during early to middle childhood, suggesting that IC processes may be particularly sensitive to external stimuli/environments during this period. Several studies have demonstrated a strong relation between early life environments and IC (Allee-Herndon & Roberts, 2019; Chen et al., 2019; Evans & Kim, 2013; Finegood & Blair, 2017; Pacheco et al., 2018). Researchers have found that moving into more impoverished

neighborhoods from less impoverished neighborhoods was associated with a significant increase in teacher-reported dysregulated behavior in children, as measured by the BRIEF teacher report (Roy et al., 2014). The same researchers discovered that the opposite was also true: moving into less impoverished neighborhoods from more impoverished neighborhoods was associated with a significant decrease in teacher-reported dysregulated behavior. Another study, which longitudinally examined the relation between family poverty and IC development, found that higher levels of poverty was associated with less improved scores on the Children's Behavior Questionnaire (CBQ) at subsequent timepoints (Moilanen et al., 2010).

As with language ability, several mechanisms have been consistently proposed to explain poverty's relationship to IC: home chaos, parental support, and exposure to toxins/nutritional deficits. It should be noted that several of the mechanisms that have been posited as potential mechanisms for poverty to IC are the same as those that have been used to explain poverty's relationship to language ability. Housing instability within the context of increased poverty has also consistently been found to be associated with lower IC behavioral performance in children (Raver et al., 2013; Roy et al., 2014; Schmitt et al., 2015). Increased years of experienced poverty and housing instability were each determined to be significant predictors of lower performance on a Flanker paradigm task in children (Raver, et al., 2013). Similarly, greater poverty and housing instability were associated with worse performance on the Day-Night Stroop task (Schmitt et al., 2015). Home chaos within the context of poverty was significantly related to worse scores on the CBQ at subsequent timepoints (Hardaway et al., 2012). Low parental support within the context of poverty was found to be associated with lower scores cross-sectionally on a Stroop task and less improvement in IC as measured by the CBQ (Moilanen et al., 2010).

To date, there are no known studies that have both neurally and behaviorally investigated IC development within the context of poverty in young children. Altered patterns of prefrontal activity during fMRI tasks have been observed in children from lower income households (Durston et al., 2002). These patterns of activity are characterized by increased prefrontal region activity overall as well as by proportionally increased activity in the dlPFC (Bruce et al., 2013; Carrion et al., 2008; Durston et al., 2002; Mueller et al., 2010; Palacios-Barrios & Hanson, 2019). Researchers have suggested that this increased activity is indicative of the increased effort/cognitive resources needed in order to perform the tasks (Bruce et al., 2013; Sheridan et al., 2012; Mueller et al., 2010). Notably, these same patterns of activation are seen when comparing younger children to adolescents and older adults (Durston et al., 2002). This makes sense, because IC processes are undergoing significant development during this period, and it is expected that performing IC tasks requires more cognitive reserve prior to maturity. For adolescents and young adults however, this pattern of activation could be reflective of relatively immature IC processes, that may be related to stunted IC maturational start points and trajectories (Casey et al., 2005). Neuroimaging research could theoretically be utilized to more definitively characterize these altered patterns of IC related brain activity in lower income children.

The reviewed literature indicates that a robust relationship exists between early poverty and IC, and that this relationship persists over time. The current study aimed to provide support for the relation between poverty and IC in the ABCD sample. To date, there are no known studies which have longitudinally examined behavioral, parent-report, and imaging modalities of IC within the context of poverty in children. Per the recommendation of Toplak et al., (2013) the current study considered each modality separately in order to gain better understanding of how

IC processes may be reflected neurobiologically, as well as how they are potentially impacting performance both under "ideal" circumstances and in more day-to-day, or "typical", circumstances. The hypotheses are:

Hypothesis 2.1: Lower SES will be associated with lower levels of IC across several modalities of assessment. Specifically:

- Lower SES will be associated with lower scores on behavioral IC tasks (Emotional Stroop and Flanker Task).
- Lower SES will be associated with lower scores on parent-report measures of IC (Early Adolescent Temperament Questionnaire [EAT-Q]).
- Lower SES will be associated with relatively greater levels of activation in the dlPFC and relatively lower levels of activation in the rIFG during a stop-signal IC task.

Hypothesis 2.2: Lower SES will be predictive of less improvement across several modalities of IC assessment over time. Specifically:

- Lower SES will predict less improvement on behavioral IC tasks across time (Emotional Stroop and Flanker Task).
- Lower SES will predict less change in terms of activation patterns in the dlPFC (relatively greater activation) and rIFG (relatively less activation) on the stop-signal IC task.

<u>Aim 3:</u> Ascertain the relationship between receptive vocabulary knowledge task performance language and different facets of IC cross-sectionally and examine the relation between receptive vocabulary knowledge and facets of IC across timepoints.

It has been demonstrated that language ability and IC share linkages to early poverty and its correlates (Allee-Herndon & Roberts, 2019; Moilanen et al., 2010; Roy et al., 2014). Also importantly, the relation between language ability and IC has been a consistent finding in the

literature. Language ability and word use in the home have been found to be strongly associated with both lower SES and variation in IC, with poorer language ability being related to more impoverished youth and poorer performance on IC tasks (Hughes, 1998; Noble, McCandliss, & Farah, 2007). Studies measuring IC often include verbal ability measures as covariates and vice versa (Blair & Raver, 2012; Carlson, 2005; Noble et al., 2005). Son et al., (2019) found that increased reading ability, but not math ability predicted IC gains at a later timepoint.

Vygotsky's (McLeod, 2020; Vygotsky & Luria, 1978) groundbreaking Sociocultural Theory of Cognitive Development emphasized interpersonal relationships and culture as being crucial in the development of cognition. He posited that social relations between humans allow for social learning. Vygotsky's theory describes a "Zone of Proximal Development" in which certain cognitive skills are attainable with the aid of more experienced society members. During early stages of social learning, older, more experienced individuals are tasked with facilitating higher order processes like self-regulation, planning, and goal pursuit in younger less experienced members. After a period of time, Vygotsky theorized that this "external" processing – which is conducted within the Zone of Proximal Development – would become an increasingly independent endeavor, a process which he termed *internalization* (McLeod, 2020; Zelazo & Frye, 1998). Vygotsky contended that humans could not develop these higher order executive functions on their own. He also emphasized that language is a crucial means through which the social learning takes place and suggested that it could be the key channel through which social learning impacts higher order cognitive development (McLeod, 2020). Vygotsky theorized that self-directed talk in early childhood was one indicator that internalization was taking place (McLeod, 2020).

Zelazo and Frye's (1998) Cognitive Complexity and Control theory, expanded upon and further specified Vygotsky's Sociocultural Theory by suggesting that improvements in particular

EF processes like IC may be explained by increased capacity for rule systems, as well as increased ability to internalize more complex rule systems. They suggested that this increased ability for rule system capacity and complexity is made possible through greater self-reflection and improved metacognition. Like Vygotsky, they theorized that increased self-reflection and improved metacognition – or internalization – is facilitated by the acquisition and mastery of language. So initially, higher order cognitive processes such as IC are facilitated through parental figures via scaffolding and social learning, then as language skill increases and children begin to engage in more self-talk, capacity and complexity for rule systems expands (Salmon et al., 2016; Vygotsky & Luria, 1978). Ultimately, the need for self-talk is diminished with increased language mastery, and greater internalization of rule systems occurs (Zelazo & Frye, 1998). Lending credence to this theory is the fact that relative gains in IC are observed after children typically learn to talk (Diamond & Taylor, 1996; Moriguchi et al., 2008). Notably, increasing complexity of language ability during early childhood coincides with the development of IC (Gagne & Saudino, 2016; Slobin, 1969). One study demonstrated that participant performance – especially the performance of younger children – on a variation of the SST was improved when they were instructed to label task stimuli and intended action (Kray et al., 2009). Winsler et al. (2000) observed that children with inhibitory problems used increased irrelevant self-talk during problem-solving in comparison to controls. On the other hand, while IC and verbal ability are frequently shown to be correlated within the literature, it is entirely possible that these constructs are developing independently, or that there is an additional overarching construct which is driving maturation of both. The current study aimed to test the hypothesis that language ability facilitates development and maturation of IC processes. The study examined receptive vocabulary knowledge and IC performance both cross-sectionally and longitudinally. By examining these longitudinal relationships, the study

endeavored to determine whether relatively better performance on this language task would predict greater improvements on IC tasks, better parent-report ratings of IC, and/or more mature patterns of activation in IC-implicated regions. The hypotheses are:

Hypothesis 3.1: Poorer performance on a receptive vocabulary knowledge task will be associated with poorer performance on inhibitory control tasks cross sectionally. Specifically:

- Worse performance on a receptive vocabulary knowledge task will be associated with lower scores on behavioral IC tasks (Emotional Stroop and Flanker Task).
- Worse performance on a receptive vocabulary knowledge task will be associated with lower scores on parent-report measures of IC (Early Adolescent Temperament Questionnaire [EAT-Q]).
- Worse performance on a receptive vocabulary knowledge task will be associated with relatively greater levels of activation in the dlPFC and relatively lower levels of activation in the rIFG on a stop-signal IC task.

Hypothesis 3.2: Poorer performance on a receptive vocabulary knowledge task will be predictive of less improvement on inhibitory control tasks over time. Specifically:

- Worse performance on a receptive vocabulary knowledge task will predict less improvement on behavioral IC tasks across time (Emotional Stroop and Flanker Task).
- Worse performance on a receptive vocabulary knowledge task will predict less change in terms of activation patterns in the dlPFC (relatively greater activation) and rIFG (relatively less activation) on a stop-signal IC task.

<u>Aim 4:</u> Determine whether language partially explains the relationship between SES and IC performance.

The established literature demonstrates a relationship between early poverty and language ability, a relation between early poverty and IC, and a relationship between language ability and IC. This pattern of consistent findings portends the existence of a mediatory effect, wherein language ability is explaining a portion of early poverty's relationship with IC performance. Few studies have attempted to make the case for language ability mediating the relationship between early poverty and IC performance. Noble et al.'s (2005) compelling findings indicated that scores on the PPVT fully explained the association between household SES and EF performance. More specifically, lower scores on the PPVT explained the association between poverty and lower performance on DOG and GNG tasks (Noble et al., 2005). Researchers emphasized that future studies should ideally use a larger sample and more comprehensive measure of poverty. It is important to note that this previous study employed a cross-sectional design and thus a longitudinal design with several repeated measures would allow researchers to determine whether temporal precedence can be established. Sarsour et al. (2011) found that measures of expressive language ability did not explain the relation between household SES and IC performance. The researchers have proposed that these expressive language assessments may not have necessarily captured child language understanding, and also highlighted that future studies should assess the variables across multiple (greater than two) timepoints to make a more convincing case for mediation (Sarsour et al., 2011).

To review, in order to more definitively make a case for mediation, it is imperative to conduct analyses using a longitudinal design wherein variables of interest are collected repeatedly across timepoints. The current study will do this using the Adolescent Brain Cognitive Development (ABCD) Study data – a large multisite study which broadly aims to better characterize different aspects of cognitive and brain development during middle childhood through

to early adulthood. Further, the large sample size (n = 11,876) with representation across the spectrum of SES will allow the researchers to more confidently predict how the hypothesized associations and mediation are delineated in the general population. Multiple indices of poverty and IC, in addition to a well-supported measure of receptive vocabulary knowledge will enable researchers to comprehensively capture constructs of interest. The hypothesis is:

Hypothesis 4.1: The relationship between baseline lower SES and less improvement on IC across modalities at subsequent timepoints will be partially explained by performance on an intermediary receptive vocabulary knowledge task.

3. METHODS

3.1 Participants

The study sample consisted of 11,876 participants from the Adolescent Brain Cognitive Development (ABCD) Study, a multisite longitudinal study which aims to generally reflect demographics of the United States. Participants were initially enrolled in the study using a predominately school-based recruitment, which primary investigators indicated would enable them to have the broadest reach (Garavan et al., 2018). The participant sample is 52% male and 65% White/Caucasian (see Table 1 for a comprehensive list of race/ethnicity percentages). Participants were nine and 10 years of age at Time 1 (Baseline) and were 13 and 14 years of age at Time 5 (Year 4 Follow-up). See Table 2 for more descriptive statistics of age (in months) at each timepoint.

Table 1

Demographic Percentages in Current Sample

Demographic Variables	Sample Percentage
Sex	
Female	48%
Male	52%
Race	
White	65%
Black	18%
Asian	6%
AIAN	3%
NHPI	<1%
Other Race	6%
Did not know/disclose	1%
Ethnicity	
Hispanic/Latinx	20%

Note: AIAN = American Indian or Alaskan Native; NHPI = Native Hawaiian or other Pacific Islander

3.2 Inclusion/Exclusion Criteria

Study inclusion and exclusion criteria were dependent upon broader criteria set by the ABCD consortium. Individuals were excluded from study participation if the child was unable to

Table 2

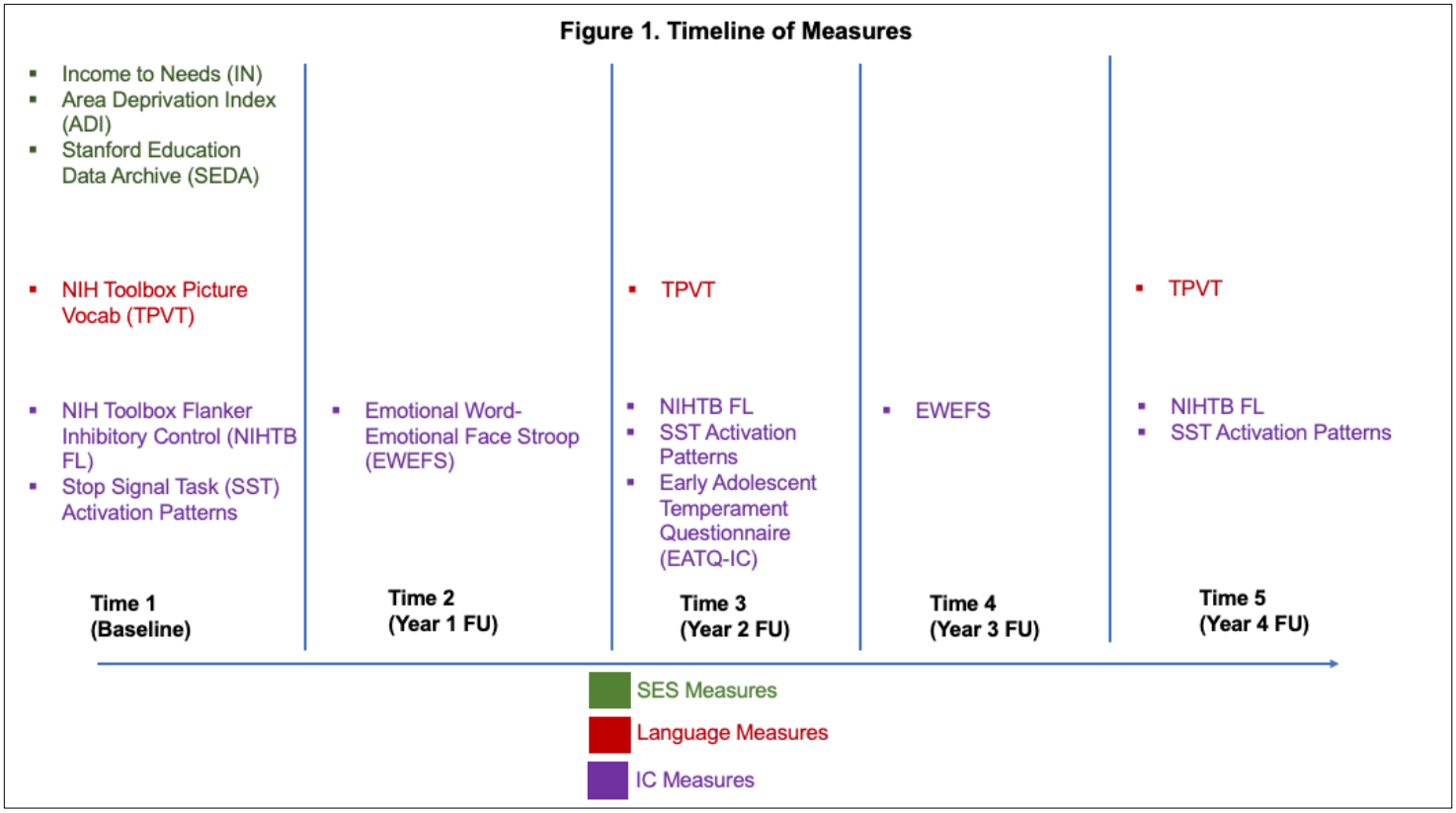
Means and Standard Deviations of Age (in Months) by Timepoint

Timepoint	Mean (SD)
Baseline	118.9 (7.50)
Year 1	131.087 (7.718)
Year 2	143.514 (7.835)
Year 3	154.714 (7.687)
Year 4	193.99 (9.143)

speak or understand English well. Children were also excluded if they had a diagnosis of intellectual disability, schizophrenia, or a neurological condition (e.g., cerebral palsy, brain tumor). Further exclusions included significantly low birth weight (less than two pounds 11 ounces), birth at less than 28 weeks gestation, current weight exceeding 250 pounds, and severe head trauma. Children were additionally excluded if they had non-removable metal or MR unsafe surgical implants, body piercings, or tattoos. Finally, participants were excluded from the MRI scan (but not from overall study participation) if they had non-removable metal orthodontia at specific timepoints.

3.3 Study Timeline

Data was analyzed across five timepoints. Child participants and their parents/primary guardians came in for study sessions once annually. Children completed questionnaires, neurocognitive tests, and/or MRI scans at each timepoint, while parents completed questionnaires



relevant to the child participant. Measures were collected at variable points across time. Figure 1 provides a more detailed layout of the study timeline.

3.4 Description of Measures

3.4.1 SES-related Measures

The study aimed to include a comprehensive measure of SES. With this in mind, the researchers determined that, in addition to income to needs (a more traditionally used SES measure), the study would include broader measures of both neighborhood SES and school SES. By doing this, the researchers intended to more effectively capture the extent of environmental deprivation.

Household Income to Needs (IN). Income to needs for each household was computed using household income and number of individuals living in the household. Household income was the parent-reported combined yearly income of the primary caretaker and any additional household members. This was a categorical variable which ranged from 1 (less than $5000 per year) to 10 ($200,000 and greater per year). The median household income for the current sample was 8 ($75000 – 90000 per year). See Figure 2 for distributions of household income and IN in the sample.

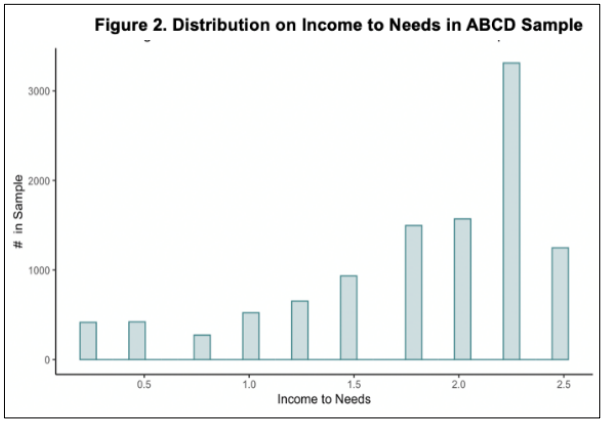


Table 3

ADI Census Variables

Variable Name
% pop. aged 25 years or older with < 9 years education
% pop. aged 25 years or older with high school diploma (R)
% employed pop. aged 16 years or older in white-collar occupations (R)
Median family income (R)
Income disparity
% families below federal poverty level
% pop. below 150% of federal poverty level
% civilian labor force pop. aged 16 years or older who are unemployed
Median home value (R)
Median gross rent (R)
Median monthly mortgage (R)
% owner-occupied housing units (R)
% housing units without complete plumbing
% single-parent households with children younger than 18
% households without a motor vehicle
% households without a telephone
% households with more than 1 person per room

Area Deprivation Index (ADI). The ADI was created by Singh (2003) to measure neighborhood disadvantage. It consists of 17 census variables which include information about census tract-level indices such as rates of unemployment, education, and poverty. The ADI enables researchers to capture degree of poverty and deprivation in surrounding

residential areas and has been demonstrated to explain variance in models above and beyond individual/household poverty measures alone (Diez-Roux, 2001; Gustafsson et al., 2014; Taylor et al., 2020). The ADI values were generated based on parent-reported residence at Time 1. The current study used the weighted sum of the 17 census variables included on the ADI (see Table 3 for a comprehensive list of ADI census variables).

Stanford Education Data Archive (SEDA). The SEDA consists of school-related variables which assess general demographic compositions of schools as well as academic achievement performance and outcomes (Ho, 2020). The ABCD Study has generated the SEDA values based on residential information reported by parents at Time 1. The specific variables from the SEDA that were used in the current study's analysis were the weighted average of proportion of students who are eligible for free/reduced lunch and the weighted average of the proportion of students who are economically disadvantaged. These variables were selected from the SEDA as they have been shown to be good indicators of whether a school has relatively fewer resources (Ho, 2020).

3.4.2 Language Measure

NIH Toolbox Picture Vocabulary Test (TPVT). The TPVT comes from the NIH Toolbox Cognitive Battery (NIHTB-CB). The TPVT is a measure of receptive vocabulary knowledge that is similar to the PPVT that has been validated in individuals aged three and older. On tests of convergent versus discriminant validity, the TPVT correlated strongly with the PPVT-IV ($r = 0.9$) and demonstrated weaker correlations with tasks such as the Brief Visuospatial Memory Test (BVMT) and Rey Auditory Verbal Learning Test (RAVLT) ($r = 0.46$ and $r = 0.42$, respectively) (Gershon et al., 2013). During the task, child participants were presented with four color images that included concrete items, activities, or more abstract

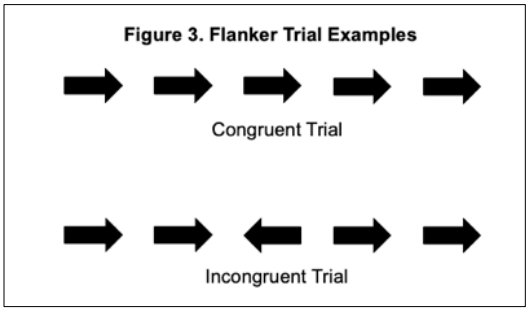
concepts (Gershon et al., 2013). While being presented with the images the participants also heard a word. Participants were instructed to point to the image on the screen that best characterized the word that they heard. The participants were able to repeat the word audio as needed. The task was administered to the child participant by an RA via iPad. Developers of the task have indicated that literacy is not needed for the task as there is no reading required and that the task is well-adapted for children because they are able to select answers without using a verbal response (Gershon et al., 2013). The uncorrected summary score was used for analyses in the current study.

3.4.3 Inhibitory Control Measures

Emotional Word-Emotional Face Stroop (EWEFS). The EWEFS has been designed to allow researchers to examine processing speed/attention, IC, and emotion processing within a given sample of children/adolescents (Smolker et al., 2022). During the task, participants were presented with an emotion word (e.g., "anger") and were simultaneously presented with the image of a face that depicted an emotion that was the same (congruent) or different (incongruent). Participants were instructed to press one button if the emotion word was "positive" and another button if the emotion word was "negative". The task was administered to the child participant by an RA via iPad. The predominant, or prepotent, impulse in this task is for individuals to respond to the faces. To respond correctly on this task, individuals must inhibit this predominant response and respond to the emotion words instead. The participants completed two blocks of this task. One block consisted of 50% congruent trials and 50% incongruent trials. The other block consisted of 75% congruent trials and 25% incongruent trials. The 75 congruent/25 incongruent block was the focus of the study's analyses, as this was the proportion of trials that is most typically seen in the literature and was most implicated in IC processing

(MacLeod, 1991; Smolker et al., 2022). In order to measure interference, the study examined the difference in reaction time (RT) and accuracy on congruent vs. incongruent trials in proportion to the RT and accuracy on congruent trials.

NIH Toolbox Flanker Inhibitory Control (NIHTB FL). The NIHTB FL task comes from the NIHTB-CB and is based on the Eriksen flanker task and is an adaptation of the version that was used on the Attention Network Test (ANT) (Akshoomoff et al., 2014; Eriksen & Eriksen, 1974; Rueda et al., 2004). The task indexes IC and selective attention by measuring interference control, or the ability to inhibit responses to conflicting or distracting stimuli (Zelazo et al., 2013). Based on task design, participants must suppress the prepotent response to match the flanking stimuli when there is a mismatch (Eriksen & Schultz, 1979).



During the task, the participants viewed a target stimulus (e.g., arrow pointing to the right) that was flanked by non-target stimuli (e.g., flanking arrows). The participants were instructed to press the button (left or right) that matched the direction of the target stimulus. For some trials, the flanking stimuli matched the target stimulus (e.g., flanking arrows pointed to the right) and sometimes they did not (e.g., flanking arrows pointed to the left). There were 40 trials total with a higher proportion of congruent vs. incongruent trials (Weintraub et al., 2013). The task was administered by an RA via iPad. The task was automatically scored using a two-vector method wherein accuracy and IC were considered in scoring for participants with greater than 80% accuracy, while participants with accuracy less than 80% were only scored based on accuracy. The uncorrected summary score was used for analyses in the current study.

Stop Signal Task (SST) activation patterns. The SST generally measures the ability to inhibit prepotent motor responses (Littman & Takacs, 2017; Montgomery & Koeltzow, 2010). It involves the presentation of left and right arrows which are occasionally interrupted by the presentation of an upward pointing arrow. Participants were instructed to press the left button when they saw a left arrow and the right button when they saw the right arrow. When the up arrow was presented, they were instructed not to press any buttons. The SST was developed based on a race model, wherein researchers theorized that simultaneous "stop" and "go" processes are "racing" against one another (Logan et al., 1984). If the "stop" process is completed after the "go" process, then the prepotent response has not been effectively inhibited. This can either be due to the "stop" process being initiated too late, being too slow, or not being initiated at all (Logan et al., 1984). The SST has commonly been used in neuroimaging studies and is associated with activation in the rIFG, a structure which has been repeatedly implicated in IC processes (Chevrier et al., 2007). The ABCD Study administered two blocks of 180 trials of the SST in the scanner. Approximately 17% of the trials consisted of "stop" trials wherein child participants were instructed to withhold a response. Child participants completed a brief practice outside of the scanner beforehand to ensure that they understood the task instructions. They were given a two-button box in the scanner to make their responses. Participants were scanned using similar sequences on either a 3T Siemens, Phillips, or General Electric scanner with a 32-channel head coil. Motion detection and correction software were used in real-time at the Siemens and GE sites. Segmentation was done using the Destrieux Atlas (Destrieux et al., 2010). For more detailed information about imaging acquisition, processing, and quality assurance procedures see Hagler et al. (2019). For more details about the SST fMRI task see Casey et al. (2018).

Concerns about some aspects of SST task design in the ABCD Study have been raised by Bisset et al. (2021). Namely, that the rule of context independence has been violated across "go" versus "stop" trials (Bisset et al., 2021). In response, Garavan et al. (2021) suggested that it is to be expected for some participants to violate the rule of context independence. Per Garavan et al.'s (2021) recommendation, the current study excluded participants who had Stop Fail RTs that were greater than Go RTs for the SST analyses. The *a priori* regions of interest were left (lIFG) and right (rIFG) IFG as well as left (ldlPFC) and right (rdlPFC) dlPFC. IFG corresponds to three bilateral regions in the Destriex Atlas: the opercular, the orbital, and the triangular part of the inferior aspect (Destrieux et al., 2010). These regions were aggregated bilaterally to compose the lIFG and rIFG. dlPFC corresponds to five bilateral regions in the Destrieux Atlas: middle frontal gyrus, middle frontal sulcus, superior frontal gyrus, superior frontal sulcus, and inferior frontal sulcus (Destrieux et al., 2010). These regions were aggregated bilaterally to compose the ldlPFC and rdlPFC. The contrast of interest was correct "stop" vs. incorrect "stop" trials during the SST. The study aimed to examine the difference in contrast between IFG and dlPFC regions bilaterally in order to determine differing patterns of region activation and accuracy across participants.

Early Adolescent Temperament Questionnaire Inhibitory Control subscale (EATQ-IC). The EATQ is a parent-report questionnaire that assesses temperament from middle childhood to middle adolescence (Rothbart et al., 2001). It is one of the series of Rothbart's Temperament Questionnaires widely used in the research literature. The questionnaire listed statements describing reactions to different situations and parents were instructed to indicate how much the reaction statement described their child on a scale from 1 ("almost always untrue of your child") to 5 ("almost always true of your child"). The Inhibitory Control subscale consists of five items.

Per Rothbart's recommendation, the total score on the Inhibitory Control subscale was the mean of the items.

Table 4

EATQ-IC Items

Item No.	Item Content
6	Has a hard time waiting his/her turn to speak when excited. (R)
8	Opens presents before s/he is supposed to. (R)
23	Is more likely to do something s/he shouldn't do the more s/he tries to stop her/himself. (R)
47	Is able to stop him/herself from laughing at inappropriate times.
59	Is usually able to stick with his/her plans and goals.

3.5 Statistical Analysis Plan

3.5.1 Intercorrelations

Intercorrelation matrices were examined to determine how the SES-measures and IC-measures could be most succinctly aggregated. Intercorrelations and factor analyses were computed and visualized using corrplot and stats packages in R (Wei et al., 2017).

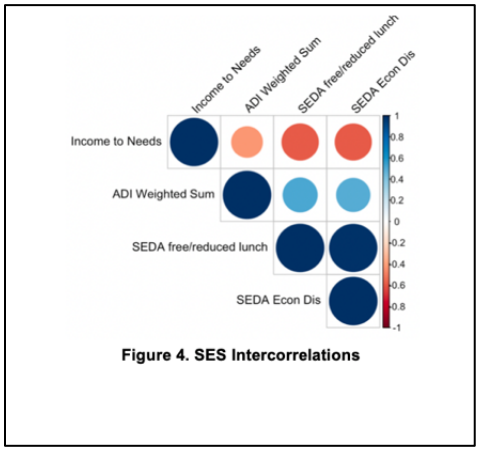


Figure 4. SES Intercorrelations

SES and SES-related Variables. The variables included were 1) income to needs, 2) ADI weighted sum total, 3) SEDA proportion of students eligible for free/reduced lunch, and 4) SEDA weighted average of the proportion of economically disadvantaged students. The results indicated that higher income to needs was negatively associated with increased neighborhood deprivation and school-related economic disadvantage as anticipated. The researchers determined that ADI weighted sum

and SEDA variables would be reverse-scored, and all SES variables were standardized and averaged for a single composite measure of SES at baseline.

IC Variables. The variables included were: 1) EWEFS accuracy (proportion congruent to incongruent), 2) NIHTB FL summary score, and 3) EATQ-IC Mean. The matrix revealed that EWEFS and NIHTB FL were moderately positively correlated with one another, while EATQ-IC Mean was not correlated with either of the behavioral tasks. This is not surprising given prior research citing low correlations between behavioral tasks and parent-report questionnaires. Further, many of the variables were collected at different timepoints. Based on these factors, the study researchers determined that each of the IC variables should be included as separate model outcomes in the analyses to allow for ease of comparison.

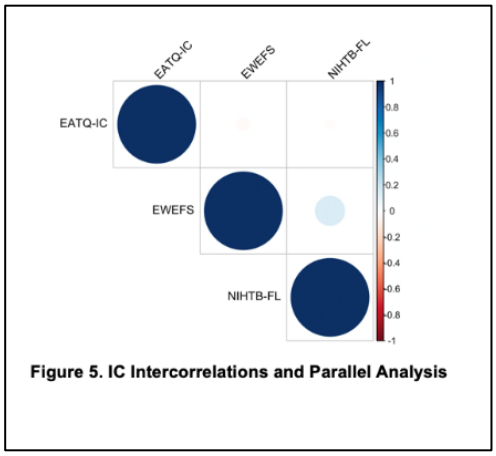


Figure 5. IC Intercorrelations and Parallel Analysis

3.5.2 Multilevel Models

The study used a linear mixed effects (aka multilevel model) approach in order to address each of the study aims. Models were computed using the brm() function within the brms package in R (Bates et al., 2014). Models were fit using the static Hamiltonian Monte Carlo sampler in Stan (Burkner, 2017). 99 % credible intervals (CIs) were examined to determine the reliability of the effects.

Aim 1: Investigate the associations between SES and receptive vocabulary knowledge performance and examine whether there are SES-associated changes in receptive vocabulary knowledge performance over time. A multilevel model was specified wherein the SES aggregate was included as the main predictor. TPVT sum scores across three timepoints were included as the

outcome. Age was centered by the initial timepoint and included as a covariate. Sex was also included as a covariate. The estimate of SES revealed whether SES was significantly related to receptive vocabulary performance across timepoints. An interaction term of age and SES was included in order to determine whether the slope of change in receptive vocabulary performance over time differed as a function of SES. Random intercepts of site and family and random slopes of individual participants over time were estimated. Finally, a separate model was computed wherein TPVT outcome was standardized based on mean score at the initial timepoint and included along with predictors of standardized (by initial timepoint) age and SES was computed to estimate coefficient effect size.

Aim 2: Investigate associations between SES and IC and determine whether there are SES-associated changes in IC performance over time. Similarly to Aim 1, multilevel models were utilized to examine relationships between early poverty and IC. The SES aggregate was included as the main predictor. Behavioral indices (EWEFS, NIHTB FL), parent-report (EATQ-IC), and brain indices (SST) were included as outcomes in three separate models. Age was centered by the initial timepoint and included in the model along with sex as covariates. The estimate of SES revealed whether SES was significantly related to IC performance across timepoints. An interaction term of age and SES was included to determine whether the slope of change in IC performance over time differed as a function of SES. Random intercepts of site and family and random slopes of individual participants over time were estimated. As with Model 1, a separate model was computed wherein IC outcomes were standardized based on mean score at the initial collected timepoint and included along with predictors of standardized (by initial timepoint) age and SES was computed to estimate coefficient effect size.

Aim 3: Ascertain the relationship between receptive vocabulary knowledge task performance and different facets of IC cross-sectionally and examine the relation between receptive vocabulary knowledge and facets of IC across timepoints. Multilevel models were utilized to examine relationships between receptive vocabulary knowledge and IC performance cross-sectionally and across time. We will use linear mixed models to predict the IC variables across ages, with TPVT as a time varying predictor (covariate), and covariates of age and sex. The IC variables that were included were behavioral indices (EWEFS, NIHTB FL), parent-report (EATQ-IC), and brain indices (SST) as outcomes in three separate models. In such a model, a main effect of TPVT in predicting IC variables will indicate a relationship of vocabulary to IC that is similar across ages. An interaction of TPVT with age was included to determine whether the relationships of between TPVT and IC would across age. Random intercepts of site and family and random slopes of individual participants over time were estimated. As with the previous models, a separate model was computed wherein IC outcomes were standardized based on mean score at the initial collected timepoint and included along with predictors of standardized (by initial timepoint) age and TPVT was computed to estimate coefficient effect size.

Aim 4: Determine whether language partially explains the relationship between SES and IC performance. Mediation analyses were be performed using the mediation (Tingley et al., 2014) package in R. SES aggregate at Time 1 were included as the predictor variable, TPVT scores at Time 2 were included as the mediating variable, and IC scores at Time 4 and 5 were included as the outcome variables. Three separate mediation models (for each modality of IC) were estimated. *a* and *b* pathways were examined to determine the indirect (mediating) effects of SES on subsequent IC performance.

4. RESULTS

4.1 Descriptive Statistics

See Table 5 for means and standard deviations (SDs) of key variables at each data wave. See Figure 6 for correlation matrix of key variables.

Table 5

Means and Standard Deviations (SD) of Key Variables by Wave

	Variable	Mean (SD)
Baseline	Income to Needs	394.36 (286.08)
	Area Deprivation Index (ADI)	94.64 (21.159)
	Prop. Free or Reduced Lunch Eligible (SEDA)	0.464 (0.285)
	Prop. Economically Disadvantaged (SEDA)	0.479 (0.288)
	NIHTB TPVT Uncorrected Score	84.456 (8.118)
	NIHTB Flanker Uncorrected Score	93.99 (9.143)
Year 1	Emotion Stroop Task Interference	0.916 (0.111)
Year 2	NIHTB TPVT Uncorrected Score	88.955 (8.519)
	NIHTB Flanker Uncorrected Score	100.143 (7.703)
	EATQ Inhibitory Control Subscale	18.807 (3.031)
Year 3	Emotion Stroop Task Interference	0.937 (0.094)
Year 4	NIHTB TPVT Uncorrected Score	93.884 (8.949)
	NIHTB Flanker Uncorrected Score	103.916 (7.741)

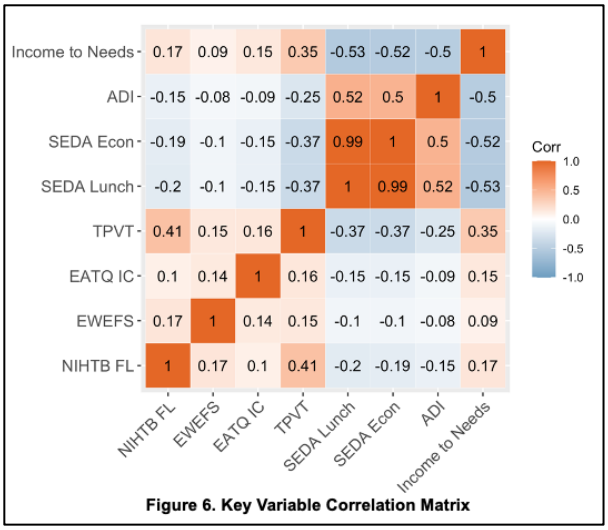


Figure 6. Key Variable Correlation Matrix

4.2 Aim 1 Results

Relations between SES and receptive vocabulary knowledge cross-sectionally and over time. As shown in Table 6, results of Aim 1 analyses revealed a main effect of SES on receptive vocabulary knowledge, wherein individuals who experienced less financial deprivation at baseline performed better on the TPVT across timepoints. Further analyses demonstrated that there was a small interaction of time (age) on SES and TPVT whereby individual with greater financial deprivation demonstrated less improvement on the TPVT at subsequent timepoints. See Figure 7 for visualization of the interaction. See Table 6 for more detailed information regarding model estimates, effect sizes, and credible intervals for Aim 1 models.

Figure 7. TPVT Scores by SES and Time (Age-Centered)

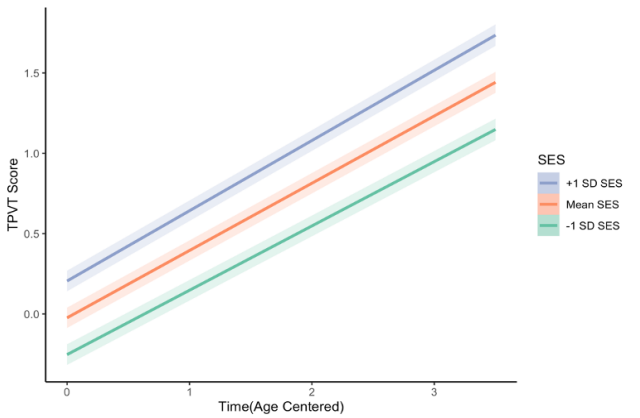


Table 6

SES by Age on Vocabulary Knowledge

	Effect Size	Credible Interval (99%)
TPVT		
SES	0.11	0.11 to 0.12
Age	0.42	0.41 to 0.43
SES x Age	0.01	0.01 to 0.01

4.3 Aim 2 Results

Relations between SES and IC cross-sectionally and over time.

4.3.1 NIHTB FL Outcome Results

As shown in Table 7, results of Aim 2 analyses, wherein NIHTB FL was included as the outcome variable, demonstrated a small main effect of SES, wherein individuals who experienced less financial deprivation at baseline performed better on the NIHTB FL task across timepoints. There was no interaction of time (age) on SES and NIHTB FL, indicating no notable differences in trajectories of NIHTB FL scores based on SES.

Table 7

SES by Age on Inhibitory Control (IC) Measures

	Standard Estimate	Credible Interval (99%)
NIHTB FL		
SES	0.06	0.05 to 0.07
Age	0.46	0.45 to 048
SES x Age	0	0 to 0.01
EWEFS		
SES	0.04	0.03 to 0.04
Age	0.13	0.1 to 0.15
SES x Age	-0.01	-0.01 to 0
EATQ- IC		
SES	0.05	0.04 to 0.06
Age	0.02	-0.01 to 0.05

4.3.2 EWEFS Outcome Results

As shown in Table 7, results of Aim 2 analyses, wherein EWEFS was included as the outcome variable, similarly demonstrated a small main effect of SES. Specifically, participants who experienced less financial deprivation at baseline exhibited better relative accuracy and faster RTs on incongruent trials across ages. Like the NIHTB FL interaction model, the EWEFS model revealed no interaction of time (age) on SES and NIHTB FL, suggesting no notable differences in EWEFS scores based on SES t.

4.3.3 EATQ-IC Outcome Results

As shown in Table 7, results of Aim 2 analyses, wherein EATQ-IC was included as the outcome variable revealed a small main effects of SES. Participants who experienced less financial deprivation were described by their parents as having better IC on this questionnaire at Time 3.

The EATQ-IC was only collected at one timepoint (Time 3) and so an interaction of time (age) on SES and EATQ-IC could not be examined.

4.3.4 SST fMRI Activation Pattern Results

Inferior Frontal Gyri. As shown in Table 8, results of Aim 2 analyses, in which right IFG and left IFG were separately included as outcome variables, revealed no main effect of SES on activation in either region. Similarly, further model results indicated no interaction effect of time (age) on SES and activation in the right IFG or left IFG.

Dorsal Lateral Prefrontal Cortices. As shown in Table 8, in which right dlPFC and left dlPFC were separately included as outcome variables, revealed no main effect of SES on activation in either region. As with the IFG, results also indicated no interaction effect of time (age) on SES and activation in the right dlPFC or left dlPFC**.**

See Table 7 and 8 for more detailed information regarding model estimates, effect sizes, and credible intervals for Aim 2 models.

Table 8

SES by Age on Bilateral IFG and dlPFC

	Standardized Estimate	Credible Interval (99%)		Standardized Estimate	Credible Interval (99%)
L IFG			**R IFG**		
SES	0	-0.01 to 0	SES	0	-0.01 to 0
Age	0.02	-0.01 to 0.04	Age	0	0
SES x Age	0	-0.01 to 0.01	SES x Age	0	0
L dlPFC			**R dlPFC**		
SES	0	-0.01 to 0.01	SES	0	-0.01 to 0.01
Age	0	0	Age	0.02	0
SES x Age	0	0	SES x Age	0	0

4.4 Aim 3 Results

Relations between vocabulary knowledge and IC cross-sectionally and over time.

4.4.1 NIHTB FL Outcome Results

As shown in Table 9, results of Aim 3 analyses, in which NIHTB FL was included as the outcome variable, demonstrated a main effect of language, wherein individuals who performed better on the picture vocabulary knowledge task also performed better on the NIHTB FL task across timepoints. The interaction model revealed a small moderation of the relationship between language and NIHTB FL by time (age), whereby the strength of the relationship decreased with age. See Figure 8 for visualization of the interaction.

Figure 8. NIHTB FL Scores by TPVT and Time (Age-Centered)

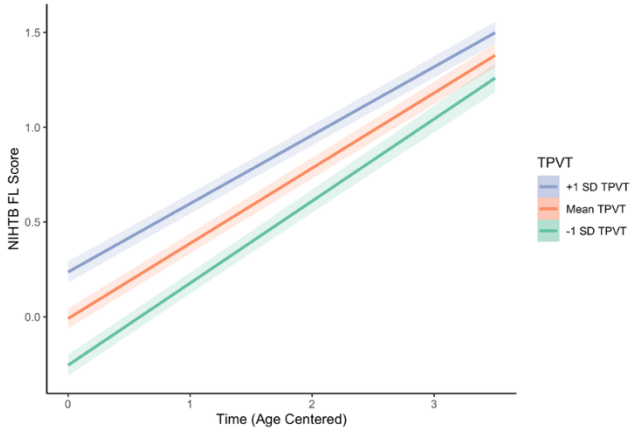


Table 9

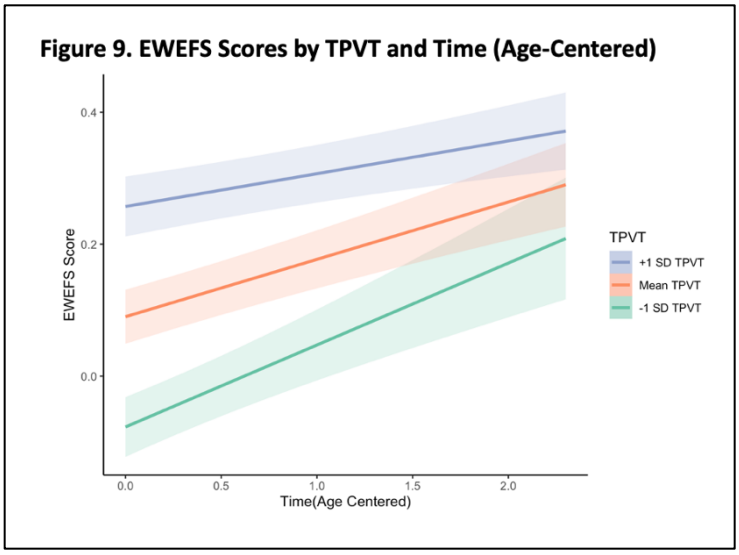
Vocabulary Knowledge by Age on IC Measures

	Standardized Estimate	Credible Interval (99%)
NIHTB FL		
TPVT	0.25	0.22 to 0.27
Age	0.4	0.38 to 0.41
TPVT x Age	-0.04	-0.05 to -0.02
EWEFS		
TPVT	0.17	0.14 to 0.19
Age	0.09	0.06 to 0.12
TPVT x Age	-0.04	-0.06 to -0.01
EATQ- IC		
TPVT	0.16	0.13 to 0.19
Age	0	-0.04 to 0.03

4.4.2 EWEFS Outcome Results

As shown in Table 9, the results of the Aim 3 analyses, wherein EWEFS was included as the outcome variable, demonstrated a main effect of SES. Specifically, participants who performed better on the picture vocabulary knowledge task also exhibited better relative accuracy and faster RTs on incongruent

trials across time points. The interaction model revealed a small moderation of the relationship between language and EWEFS scores by time (age), whereby the strength of the relationship decreased with age. See Figure 9 for visualization of the interaction.



4.4.3 EATQ-IC Outcome Results

As shown in Table 9, the results of Aim 3 analyses, wherein EATQ-IC as the outcome variable, revealed a main effect of picture vocabulary knowledge performance. So, participants who performed better on the picture vocabulary knowledge task were described by their parents as having better IC on this questionnaire at Time 3. The EATQ-IC was only collected at one timepoint (Time 3) and so an interaction of time (age) on picture vocabulary knowledge and EATQ-IC could not be examined.

Table 10

Vocabulary Knowledge by Age on Bilateral IFG and dlPFC

	Standardized Estimate	Credible Interval (99%)		Standardized Estimate	Credible Interval (99%)
L IFG			**R IFG**		
TPVT	0	-0.02 to 0.02	TPVT	0	-0.02 to 0.03
Age	0.01	-0.02 to 0.03	Age	0	-0.01 to 0.01
TPVT x Age	0.01	-0.01 to 0.03	TPVT x Age	0	-0.02 to 0.03
L dlPFC			**R dlPFC**		
TPVT	0.02	0 to 0.04	TPVT	0.01	-0.01 to 0.04
Age	0.01	-0.01 to 0	Age	0.01	0 to 0.07
TPVT x Age	0.01	-0.01 to 0.03	TPVT x Age	0.01	-0.01 to 0.03

4.4.4 SST fMRI Activation Pattern Results.

Inferior Frontal Gyri. As shown in Table 10, the results of Aim 3 analyses, in which right IFG and left IFG were separately included as outcome variables, revealed no main effect of picture vocabulary knowledge on activation in either region. Similarly, further model results indicated no interaction effect of time (age) on picture vocabulary knowledge and activation in the right IFG or left IFG.

Dorsal Lateral Prefrontal Cortices. As shown in Table 10, there was no main effect of picture vocabulary knowledge on activation in either right dlPFC and left dlPFC . In addition, there was no interaction effect of time (age) on picture vocabulary knowledge and activation in the right dlPFC or left dlPFC**.**

See Tables 9 and 10 for more detailed information regarding model estimates, effect sizes, and credible intervals for Aim 3 models.

4.5 Aim 4 Results

Mediation analyses examining whether picture vocabulary knowledge partially explains the relationship between SES and IC performance. Mediation analyses were conducted for NIHTB FL outcome and EWEFS outcome. Mediation was not examined for the EATQ-IC outcome because data was only assessed across two timepoints. Mediation was also not examined for either IFG or dlPFC outcomes because there was no demonstrated relation to SES or TPVT.

Table 11

Mediation of TPVT on Early SES and Flanker Performance

	Estimate	Effect Size	Credible Interval (95%)
Outcome: NIHTB FL **Mediator: TPVT** **Predictor: SES**			
Direct Effect (ADE)	0.36	0.04	0.29 to 0.43
Indirect Effect (ACME)	0.26	0.03	0.23 to 0.29
Mediator Effect	0.22	0.21	0.2 to 0.24
Total Effect	0.62	0.06	0.55 to 0.69

Note: Proportion mediated: 41.81% credible interval (35.78% to 47.91%)

4.5.1 NIHTB FL Mediation Results

Mediation results revealed an indirect effect of SES on NIHTB FL through TPVT in which the proportion mediated was 41.81% (95% CI [35.78%, 47.91%). See Table 11 for estimates and credible intervals of other mediator effects.

Table 11: Mediation of TPVT on Early SES and Flanker Performance

4.5.2 EWEFS Mediation Results

Mediation results revealed an indirect effect of SES on EWEFS through TPVT in which the proportion mediated was 42.79% (95% CI [20.37%, 65.22%]). See Table 12 for estimates and credible intervals of other mediator effects.

Table 12

Mediation of TPVT on Early SES and Emotional Stroop Performance

	Estimate	Effect Size	Credible Interval (95%)
Outcome: NIHTB FL **Mediator: TPVT** **Predictor: SES**			
Direct Effect (ADE)	0.002	0.02	0.001 to 0.003
Indirect Effect (ACME)	0.001	0.01	0.001 to 0.002
Mediator Effect	0.001	0.09	0.001 to 0.002
Total Effect	0.003	0.03	0.002 to 0.004

Note: Proportion mediated: 42.79% credible interval (20.37% to 65.22%)

5. DISSCUSSION

The broad aim of the current study was to determine how early poverty, language, and IC were interrelated concurrently and across time, and to more specifically elucidate whether language performance was key in explaining the hypothesized relation between early poverty and subsequent IC performance.

The study's results demonstrated a relation between early financial deprivation and performance on the TPVT in which children who experienced increased early financial deprivation at baseline measurement had worse performance on the TPVT across timepoints. Additionally, children who experienced greater financial deprivation at baseline exhibited less improvement on the TPVT task at subsequent ages when compared to children who experienced less financial

deprivation. These findings support the Aim 1 hypotheses. These findings are also consistent with recent literature that has highlighted the relationship between access to and/or availability of environmental resources and language development (Dollaghan et al., 1999; Guo & Harris, 2000; Justice et al., 2020; Lurie et al., 2021 Patra et al., 2016; Zambrana et al., 2012). Crucially, the current study's findings provide evidence to support the idea that not only do individuals experiencing increased financial deprivation have attenuated developmental trajectories over time, but that they may also have less subsequent improvement, thus further exacerbating developmental disparities. It is important to note that the effect size for the relation between early poverty and TPVT was small, however, the large and representative study sample increases confidence that this effect would be present in the general population. The effect size for the interaction of financial deprivation and time (age) on TPVT was considerably smaller than the main effect of financial deprivation on TPVT. This small effect could be partially due to the relatively small improvements in TPVT performance across the entire participant sample. In normative cases, the most significant strides in language development occur by age six (NIDCD, 2022). After this, continued development in the form of refinement and increasing complexity occurs more gradually. It is possible that a more complex language task would allow the researchers to more effectively observe subtle developmental changes after six years of age. Alternatively, conducting the study with a younger participant sample (i.e., less than six years of age) could potentially reveal stronger effects of financial deprivation on language as this is the period in which the most notable developmental gains occur.

Study findings also revealed a relation between early financial deprivation and performance on the NIHTB FL and EWEFS tasks. There was no time (age) interaction on the relationship between early financial deprivation and NIHTB FL or EWEFS task performance.

There was a relation between early financial deprivation and scores on the EATQ-IC. For all three of these measures, greater early financial deprivation was associated with worse performance on the inhibitory control tasks and lower parent-ratings of inhibitory control. These findings generally support the Aim 2 hypotheses. As aforementioned, several other studies have shown that different facets of SES have been concurrently associated with or have prospectively predicted later IC performance (Hardaway et al., 2012; Moilanen et al., 2010; Raver et al., 2013; Roy et al., 2014; Schmitt et al., 2015). Concordance across behavioral and parent-report modalities suggests that early financial deprivation impacts both experimental and day-to day contexts. Experimental settings are generally thought of as standardized environments, in which experimenters and researchers can get a more precise measure of general IC function without as much influence of other executive function processes or distracting stimuli. These experimental settings are often distinct from more realistic day-to-day settings such as classrooms where there can be distracting stimuli (e.g., other children, noises, etc.) in addition to more complex tasks to attend to (e.g., paying attention to what the teacher is saying as well as writing on the board). However, parent-reported indices of IC are likely more ecologically valid because they are providing increased insight into how children are navigating day-to-day activities that require IC. Taken together, concordance across modalities increases researcher confidence in the findings' reliability and generalizability.

Conversely, there were not associations of early financial adversity with brain-related indices of IC and other IC measures, which was counter to the current study's hypotheses. Several possible reasons exist for the lack of association between financial deprivation and activation in brain-related regions. One primary explanation could be the potential difficulties with test-retest reliability frequently seen in task-based fMRI studies – particularly in studies focusing on children and adolescents (Bennett & Miller, 2013; Herting et a., 2018). In cases where test-retest reliability

is a concern, some researchers have suggested that using a voxelwise approach instead of anatomically-based ROIs may be preferred (Britton et al., 2013; Herting et al., 2018). It is also possible that scanner harmonization across sites was not as effective for the Stop Signal Task relative to the other fMRI tasks.

In addition, the lack of interaction of time on the relationship between early financial deprivation and behavioral IC tasks was not as hypothesized, although we did see such an interaction for language function. As with language, the majority of notable developmental IC milestones have likely occurred prior to baseline age of ABCD study participants. Similar to the language measures, utilizing a more complex IC task (which could additionally index other aspects of executive function such as flexibility/switching) or conducting the study with a younger participant sample could potentially reveal stronger effects of financial deprivation on IC over time.

Study results further indicated a relation between TPVT scores and performance on the NIHTB FL and EWEFS tasks. In addition, there was an interaction of time (age) on the relation between TPVT and behavioral IC performance. Specifically, children who had higher initial TPVT scores had better IC performance at later ages. Study results also demonstrated a relation between TPVT scores and parent-reported IC on the EATQ-IC. These findings provide support for the Aim 3 hypotheses. These findings are consistent with aforementioned literature which has shown that language understanding is correlated with IC performance (Hughes, 1998; Noble, McCandliss, & Farah, 2007; Son et al., 2019). These results also provide evidence to support Vygotsky's Sociocultural Theory as they indicate that preceding vocabulary knowledge was related to subsequent IC and IC change. It is possible that greater vocabulary knowledge is allowing for better internalization of rule systems and leading to relatively improved IC functioning and self-

regulation as Vygotsky and colleagues theorized. Additional studies are needed to more explicitly measure how or whether language (particularly semantic understanding and the employment of overt self-talk) is impacting understanding of these regulatory rule systems in young children. The current study findings further demonstrate evidence to suggest that language may have an impact on IC developmental trajectories not just initially, but may continue to alter trajectories across time. This highlights the importance of early and recurrent intervention in cases where language deficits are observed. Similarly, to Aim 1, the effect sizes for both the main effects and the interactions were small. As with Aim 1, the small improvement in TPVT and IC could be reflective of the gradual refinement of language and IC performance at that particular developmental stage. Again, it is possible that more complex language and/or IC tasks could yield more pronounced effects.

On the other hand, consistent with the results of analyses for Aim 2, there was no relation between TPVT performance and activation in bilateral IFG or dlPFC, which countered the study's hypotheses. Potential issues related to test-retest reliability and scanner harmonization are similarly relevant here.

Finally, mediation analyses indicated an indirect effect of TPVT at Time 2 on the relation between financial deprivation at baseline and behavioral IC performance at Time 4. Thus, children who experienced increased financial deprivation had reduced performance on the TPVT at subsequent timepoints, and this reduced TPVT performance partially explained subsequent reduced performance on the NIHTB FL and EWEFS tasks. These findings provide evidence to support Aim 4 hypotheses. Prior research studies have shown independent relationships between early financial deprivation and language, between language and IC, and between early financial deprivation and IC. Some prior studies have also used a cross-sectional design to identify evidence

for language as a mediator of SES and IC (Noble et al., 2005). This is the first known longitudinal research study to provide evidence for a mediating effect of language on the relationship between early financial deprivation and IC in children.

While the reviewed literature indicates that researchers have more recently begun to focus on cognitive development within impoverished environments, the literature is still largely lacking with regard to research in these populations. The current study provides increased clarity about the nature of the relationship between early to middle life poverty, language ability, and IC. Though the observed effect sizes were small, the current study, along with further targeted research, could potentially allow for more informed decisions to be made concerning early childhood intervention and could lead to the mitigation of negative outcomes commonly experienced within the context of childhood poverty. For example, if augmenting language ability is definitively identified as a means through which to enhance IC, then interventions targeting language ability (and IC indirectly) would be well-warranted.

Study Limitations

While the current study possesses several strengths (e.g., multiple modalities of IC measurement, large and broadly representative sample, repeated collection across several timepoints, etc.) it is important to note key study limitations and discuss how they may have impacted overall implications and interpretation of findings.

Use of pre-existing data. Although the ABCD Study has provided a rich dataset that includes several key measures across multiple timepoints, one key limitation of the current study is that the researchers did not have direct input on the study design, and thus the ABCD Study was not explicitly designed to test the current study's research questions. The current study is limited to the measures that the ABCD Study has included in their protocol. The subsequent limitations

are largely related to this broader limitation. It is worth stating that while the researchers did not have direct input, the ABCD Study was designed to widely capture cognitive development in a representative sample of children and adolescents and is thus an ideal dataset in which to do secondary analysis for the current study.

Data missingness related to the COVID-19 pandemic. It is important to note that the ABCD study data was collected virtually for a period of time due to the COVID-19 pandemic. While the current study generally had access to a large dataset with several observations per study participant, certain tasks such as the NIHTB-FL were not able to be collected virtually while ensuring task fidelity. Limited observations for these tasks impacted the statistical analysis chosen for the current study and task with fewer assumptions was selected to allow for the most accurate estimation of parameters.

Circumscribed language measure. Crucially, the study only had access to one measure of receptive language across timepoints. The TPVT – along with receptive vocabulary knowledge tasks on the whole – has been established as a reliable predictor of IQ, as well as an indicator of broader language function/understanding. However, multiple and more in-depth indices of language function (semantic understanding, narrative language measures, etc.) would be more ideal. When interpreting study results, it is important to use caution and to note that, although the TPVT may be indicative of other indices of language function, it is a singular measure which is likely not encompassing the multifaceted construct of language ability.

Earlier measures of poverty may not be accurate. As aforementioned, the ABCD Study began data collection when participants were 9 and 10 years of age. Parents did not provide retrospective information on household income. Therefore, it is possible that families' preceding financial situations were different from what they reported at Time 1. It would be ideal to capture

a measure of SES for all years of the child's life, in order to better ensure the most accurate conceptualization of the family's financial picture. While this retrospective information was not gathered, it is important to note that financial situations of families have generally not been to shown to significantly change across time (Devine et al., 1992).

Future Directions

The current study's findings highlight the importance of continued research to understand how environmental deprivation impacts children's cognitive development. As aforementioned, children from financially impoverished households are generally understudied, and this is especially the case for children of color and children from non-Western cultural backgrounds. Recruitment of individuals from impoverished households can be more challenging due to several factors such as increased time demands, difficulties with transportation, and potential reduced familiarity with research studies and respective institutions. However, it is crucial to conduct research in these populations in order to increase confidence in the generalizability of prior research and to provide insight which can be used to promote the further development of effective early interventions. Future research should aim to center individuals from diverse financial, racial, and cultural backgrounds.

One major limitation of the current study was the circumscribed language measure. Future research should aim to collect several language measures which index facets of expressive and receptive language. Importantly, Vygostkian researchers have pointed to self-talk during play as being key in leading to internalization of regulatory rules (Fahy, 2014; Zelazo & Frye, 2014). Several previously conducted observational studies have demonstrated that use of private speech in children was associated with better self-regulatory behavior and performance on tasks requiring rule-learning and planning (Berk & Pottts, 1991; Lidstone et al., 2010). Future studies may benefit

from the addition of an observational measure in which researchers are directly assessing both the quantity and quality of self-talk in more naturalistic environments.

Overall, the study findings are consistent with aforementioned literature which has shown that language understanding is correlated with IC performance (cite). These results also provide evidence to support Vygotsky's Sociocultural Theory as they indicate that preceding vocabulary knowledge was related to subsequent IC and IC change. It is possible that greater vocabulary knowledge is allowing for better internalization of rule systems and leading to relatively improved IC functioning and self-regulation as Vygotsky and colleagues theorized. Additional studies are needed to more explicitly measure how or whether language (particularly semantic understanding and the employment of overt self-talk) is impacting understanding of these regulatory rule systems in young children. The current study findings further demonstrate evidence to suggest that language may have an impact on IC developmental trajectories not just initially, but may continue to alter trajectories across time. This highlights the importance of early and recurrent intervention in cases where language deficits are observed.

One example of such an intervention is Tools of the Mind. Tools of the Mind is an intervention program that was developed by Bodrova and Leong (2006) for the purpose of facilitating development of self-regulatory functions (with an emphasis on IC) in early childhood. The program is based on Vygotsky's Sociocultural Theory of Development which highlights the importance of social learning and language in cognitive development (Vygotsky & Luria, 1978). For preschool-aged children, Tools of the Mind utilizes make-believe and pretend play to encourage usage of self-regulation strategies. For kindergarten-age children, the program focuses more on emphasizing development of self-regulation within the context of different academic subjects (e.g., Scaffolded Writing). In a randomized clinical control trial, Solomon et

al. (2017) found that preschool-aged children who underwent the Tools of the Mind program, and who were rated by parents as having difficulties with attention, demonstrated improvements on an IC task when compared to children who completed a general pretend play curriculum. Another randomized control trial found that kindergarten children who took part in Tools of the Mind curriculum demonstrated improvements in reading and writing performance, as well as improvements in executive function when compared to kindergarten children enrolled in workshops (Diamond et al., 2019). Barnett et al. (2008) found that a classroom which had implemented Tools of the Mind reported less behavior issues, explained by reductions in externalizing and internalizing behaviors, in comparison to a classroom which employed the typical curriculum. Notably, the children in this classroom came from less resourced backgrounds, suggesting that this curriculum could be beneficial for individuals regardless of socioeconomic status. Additional randomized clinical control trials should be conducted centering on individuals from impoverished backgrounds in order to determine whether this curriculum can be consistently and effectively implemented in lower resourced schools.

Conclusion

Overall, the study findings point to the importance of language learning and understanding in the use of self-regulatory processes such as IC, and further demonstrate how these processes can be attenuated when individuals are placed in financially deprived environments. As work in the field of developmental cognitive neuroscience continues to expand, additional research should aim to continue characterizing how trajectories may differ based on environmental circumstances and within other historically unresearched demographics in order to move toward an all-encompassing understanding of cognitive processes across the lifespan.

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