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The current study examined developmental changes in electrophysiological indices of frontal cortical maturity across the toddler years and assessed how variation between children in the initial level and amount of change were associated with variation in their inhibitory control (IC) abilities in preschool. Additionally, to provide information about the role of language in the development of IC, the study also examined children's speech during problem-solving at 3 years and assessed how variation between children in the overall amount and content of their private (i.e., self-directed) and social speech in this context were associated with variation in their IC. Finally, the current study assessed whether the amount of speech during problem-solving was a mediating mechanism through which the overall level of frontal cortical maturity across the toddler years was associated with children's IC in preschool.

One-hundred and eighty children (54% male) participated in the study. Frontal cortical maturity was assessed from resting-state electroencephalography (EEG) at 10, 24, and 36 months; spectral power (6-9 Hz) at frontal scalp sites was computed and averaged to yield composites. Children's problem-solving speech was observed at 3 years from a challenging puzzle task; mothers were nearby but unavailable to help. Utterances were transcribed and coded based on orientation (social vs. private) and content. Children's IC was assessed at 4 years from a battery of observational tasks and surveys completed by mothers and experimenters. Frontal EEG power composites were modeled

in a growth curve using structural equation modeling; associations between individual variation around growth parameters (intercept, slope), speech variables, and IC were examined in Mplus.

Results indicated that there was significant, positive linear change in children's resting frontal EEG power values from 10 months to 3 years, suggesting this is a period of maturational growth in the frontal cortex. Although a significant amount of variance in the initial level (intercept) and amount of change (slope) were observed, it was not associated with variation in children's IC at age 4 or in the amount of speech they produced during problem-solving at age 3. However, the amount of speech children produced during problem-solving was significantly negatively associated with their IC, suggesting that young children who are more vocally reactive to challenges (e.g., frustration) may have lower IC in the preschool period. Additionally, the proportion of children's private speech that was 'mature' (i.e., semantically on-task, coordinated with task-relevant manual actions) was positively associated with their IC, which is consistent with theory and previous research. Finally, a significant positive association between the proportion of children's social speech that was classified as 'help-seeking' and their IC was observed, suggesting that motivation to comply with adults' requests is an important factor in this developmental process. Collectively, these findings suggest that characteristics of young children's speech during problem-solving at 3 years help explain variance in their IC skills at age 4, but that additional research is needed to understand the underlying mechanisms and the role of children's frontal cortical maturity.

DEVELOPMENTAL CHANGES IN ELECTROPHYSIOLOGY AND

SPEECH DURING PROBLEM-SOLVING AS PREDICTORS

OF INHIBITORY CONTROL IN PRESCHOOL

by

Margaret Whedon

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Approved by

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APPROVAL PAGE

This dissertation written by MARGARET WHEDON has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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CHAPTER I

INTRODUCTION

Children's ability to effectively modulate their internal states and responses to eliciting events in accordance with situational demands (i.e., self-regulation) is critical for their well-being and psychosocial adjustment across the lifespan. Inhibitory control (IC), the ability to suppress or temporarily withhold inappropriate behavior, is a central component of self-regulation that develops early in life and contributes to multiple aspects of adaptive functioning. For instance, to pay attention in class children may need to avoid looking at irrelevant or distracting events (e.g., noise, friends). Similarly, to get along with teachers and peers, children may need to avoid responding automatically to conflicts in ways that are rude or offensive (e.g., arguing, hitting) and instead respond in ways that are more prosocial. IC becomes particularly important for children as they enter school, where they will be expected to remain engaged with lessons, get along with others, and follow a variety of different rules.

Although rudimentary forms of IC can be observed in infancy, it is not until the preschool period that children can selectively attend or inhibit actions from verbal instructions or commands. Early deficits in 'verbally-mediated' IC (e.g., delaying gratification upon request, following complex rules) have been associated with stable trajectories of behavior problems (e.g., misconduct, aggression, hyperactivity) across childhood (Perry, Calkins, Dollar, Keane, & Shanahan, 2017; Utendale, Hubert, Saint-

Pierre, & Hastings, 2011). Thus, identifying factors that may account for individual differences in IC in the preschool period is an important aim for research.

Self-Regulatory Development

Self-regulation is thought to involve a set of integrated processes that operate at multiple levels of analysis (i.e., biological, psychological, behavioral; Calkins & Fox, 2002). Early biological functioning, because it may constrain or facilitate subsequent psychological or behavioral functioning, is thought to serve a foundational role in the development of individual differences in self-regulation (Calkins, 2007). One biological system likely to serve as a foundation for children's IC is the cerebral cortex, a collection of folded tissues forming the exterior layer of the brain where active forms of thinking and information processing occur. In early development, different regions of the cortex become specialized for processing different kinds of information. Posterior cortical areas, for instance, are specialized for visual and other sensory processing very early in life (Johnson, 1990). However, the frontal cortex matures more gradually, and becomes specialized for 'higher-order' cognitive processes (e.g., working memory, action planning), which are important for responding effortfully and appropriately in novel or challenging contexts. Because learning to inhibit behavior appropriately across contexts may crucially depend on the availability of neural resources in the frontal cortex, maturational growth in the frontal cortex across the first few years of life may represent a biological foundation for IC skills (Diamond, 2002).

In addition to having a biological foundation, self-regulation abilities are understood to develop as a result of experiences, which are shaped by multiple factors.

Although most research has defined experience in terms of extrinsic factors outside the child (e.g., caregiving), children's own behaviors necessarily contribute, and may serve an active role in shaping the kinds of experiences they have and skills they develop (Gottlieb, 2007). Gottlieb's research with animals demonstrated that self-stimulating behaviors and self-generated experiences were important for the emergence of a variety of traits and abilities (see Michel, 2007). One behavior that may be considered self-stimulating or self-generated and that may play a similarly active role in the development of children's IC is speech. Specifically, the speech children produce in response to conflicts and challenges may contribute to how they think in these situations over time. According to one theory, the private (i.e., self-directed) speech children produce during problem-solving in the early preschool period becomes internalized as 'inner speech,' a cognitive function associated with action planning (Vygotsky & Luria, 1994). Thus, whereas maturation of the frontal cortex may serve as a biological foundation for IC by providing the neural resources for working memory (WM), children's private speech during problem-solving may further contribute by influencing their ability to use language internally in situations when IC may be needed.

Although it is not often discussed in the child development literature, the frontal cortex is also thought to be important for speech. Thus, individual differences in children's problem-solving speech (e.g., the overall amount) may also be associated with their frontal cortical maturity. As the last neural system to mature in development, the frontal cortex is ultimately responsible for regulating the activity of other cortical regions and suppressing the activity of 'lower-level' neural systems via cortical inhibition (Lewis, 2005). The limbic system, a collection of structures directly beneath the frontal cortex that are important for emotion and motivation, is likely to be activated during problem-solving, and 'bottom-up' projections from the limbic system to the frontal cortex may promote speech in this context. Because they may have less inhibition over limbic system activity, children whose frontal cortices are relatively less mature may produce the greatest amount of speech during problem-solving. Thus, although children's frontal cortical maturity and speech during problem-solving may be independently associated with IC, they may be associated with one another.

In this chapter, I review the developmental time course of IC and discuss theoretical perspectives on its development, highlighting the roles of frontal cortex maturation and private speech; relevant empirical works are reviewed in detail. Subsequently, I discuss how children's frontal cortical maturity may be associated with the amount of speech they produce during problem-solving. In the next chapter, aims and hypotheses for the study, in which the amount of speech during problem-solving at 3 years is examined as a mediator linking the overall level of frontal cortical maturity across the toddler years to IC at 4 years, are discussed.

The Development of Inhibitory Control

Experimental research with infants and young children suggests that IC develops gradually, with important changes occurring towards the end of the first and fourth years of life. To investigate the emergence of IC in human development, Diamond (1985) charted the progression of infants' performance on Piaget's A-not-B task across the latter half of the first year. In this task, infants watch as a toy is hidden under one of two buckets (A, B); after a brief delay, they are encouraged to search for the toy. After two successively correct reaches towards location A, the researcher (in plain view of the infant) hides the toy under the other bucket (B). Infants less than 8 months often erroneously reached towards A despite having seen the toy being hidden under B; although, incorrect searches became increasingly less frequent towards the end of the first year. Subsequent studies indicated that the length of delay infants could tolerate while still achieving success increased with age (Marcovitch & Zelazo, 1999). Collectively, this work suggested that infants become increasingly capable of inhibiting inappropriate behaviors based on contextual information held in WM towards the end of the first year.

Diamond continued to study the development of IC in young children using experimental tasks that required inhibition of a dominant behavioral response. However, once children could understand spoken language, language became a central feature of the paradigm. In the Day–Night task (Gerstadt, Hong, & Diamond, 1994), children were instructed to say ‘Day’ when presented with a picture of a moon and to say ‘Night’ when presented with a picture of a sun, which required them to inhibit the prepotent response to label what was depicted on the cards and instead refer to them with the opposite labels. Thus, like the A-not-B task designed for infants, the Day-Night task required children to inhibit behavior based on information held in WM (the task rules). Using this task with 3- to 7-year-olds, it was found that many children started out responding correctly but began labeling the pictures they saw on the cards (i.e., perseverating) in the midst of trials. Additionally, however, many young children simply refused to play by such ‘silly’ rules or responded with the same word for each trial. On average, children did not do well with this task until 4.5 years of age.

Other studies using similar paradigms have reported rapid improvements in verbally-mediated (i.e., rule-based) IC across the fourth year. Using a ‘Simon Says’ task, Jones, Posner, and Rothbart (2003) instructed children to follow the commands given by one puppet (e.g., *Touch your nose*!) but to ignore the instructions given by another puppet. Although very few (22%) children 36 through 38 months of age were able to inhibit responding to the second puppet’s commands, children 39 to 41 months did so 76% of the time. Earlier research using this task similarly found rapid improvements between 3.5 and 4 years (Reed, Pien, & Rothbart, 1984). In Luria’s ‘Hand Game’ (Luria, Pribram, & Homskaya, 1964), an experimenter makes one of two hand gestures (fist or flat) and instructs children to respond with the opposite gesture across a series of trials. Although 3-year-olds’ performance on this task has typically been at chance, 4-year-olds have responded correctly on most trials (Hughes, 1996; 1998).

Collectively, this work suggests that children’s capacity for IC emerges first in rudimentary form in infancy before coming online more fully in early childhood. Specifically, towards the end of the first year, infants become increasingly capable of inhibiting inappropriate behaviors (e.g., reaching for objects) in accordance with their own visual-based knowledge and goals (information held in spatial WM). However, it is not until the end of the fourth year that children reliably demonstrate a capacity to inhibit behaviors in accordance with rules and verbal commands. Although the protracted maturation of the frontal lobe is widely recognized as being important for this developmental process, the role of children's emerging language skills is not yet clear.

Frontal Cortex Maturation and the Development of Inhibitory Control

Prior to Diamond's behavioral research with human infants, Goldman-Rakic had been investigating the neural correlates of spatial WM in Rhesus monkeys using Piagetian-like tasks. Like A-not-B, in the Delayed Response task, monkeys are trained to search for a hidden reward (food morsel) after a brief delay (unlike A-not-B, the location of hiding is random vs. based on subjects' previous response). Using surgical ablation techniques, Goldman and Rosvold (1970) showed that monkeys with lesions to the dorsolateral prefrontal cortex (PFC), but not other cortical regions, repeatedly failed this task at delays of as short as two seconds. Subsequently, using single-cell recording techniques with a computerized version of the task, Kojima and Goldman-Rakic (1982) found that neurons in the dorsolateral PFC selectively increased their firing rates during the delay phase of the task, suggesting they were 'holding' the goal-relevant visual information online for temporary use. This work was groundbreaking and suggested there was a cellular basis of spatial WM in the frontal cortex.

Because infants' IC skills may draw upon their WM resources, Diamond (1988) thought that frontal cortex function was similarly important for human infants' IC abilities. However, because the Delayed Response task was not a measure of IC per se (hiding location was random), and because Goldman-Rakic's neuroscience techniques were not viable for use with human infants, to provide support for her hypothesis, Diamond and Goldman-Rakic (1986, 1989) trained Rhesus monkeys on the classic A-not-B task and investigated the effects of brain lesions on their performance. As in earlier work, adult monkeys that received lesions to the PFC, but not the parietal cortex or hippocampus (other brain regions associated with learning and memory), exhibited deteriorated task performance in the form of disinhibited, perseverative responding (Diamond, Zola-Morgan & Squire, 1989). That PFC-lesioned monkeys exhibited comparably impaired performance on the A-not-B task as did human infants less than 8-12 months of age provided initial support for Diamond's (1988) view that maturation of the frontal cortex in early life serves a foundational role in the development of IC.

Cortical maturation is a complex developmental process characterized by changes in the size, composition, and function of cortical tissues. One aspect of cortical maturation that has been studied extensively in mammals is synaptogenesis, the 'blooming and pruning' of synapses, connections between neurons that support information processing. Across species, a common pattern is reported characterized by synaptic overproduction in early postnatal development followed by a prolonged period of synaptic elimination. For example, synaptic density in the cortices of monkeys increases for the first month after birth, reaches peak levles around 2 months before slowly declining (Rakic, Eckendorf, Zecevic, & Goldman-Rakic, 1986). In humans, however, this process is *protracted*, such that posterior cortical regions begin maturing earlier than anterior regions. Specifically, in the visual cortex, synaptic density is near adult levels shortly following birth, increases rapidly between 2 and 4 months, and reaches peak levels around 8 months (Huttenlocher, de Courten, Garey, & van der Loos, 1982; Huttenlocher & de Courten, 1987). In contrast, synaptic density in the frontal cortex increases dramatically towards the end of the first year, and maximal levels are not observed until after 15 months (Huttenlocher, 1979; Huttenlocher & Dabholkar, 1997).

Greenough and his colleagues (1987) speculated that maturational brain growth serves a foundational role in the emergence of skills. In line with this theory, the age at which Rhesus monkeys could first achieve success on Piaget's A-not-B task was between 2 and 4 months (Diamond & Goldman-Rakic, 1986), around the same time synaptic densities were observed to peak across all regions of the monkey cortex. Comparatively, human infants' performance on this task improves towards the end of the first year, when synaptic density in the frontal cortex was observed to first exceed adult levels. The protracted course of human brain development may partially account for the increasing sophistication of IC skills across early childhood in our species. Additionally, because learning to inhibit behavior appropriately across contexts may involve WM, variation in the amount or rate of synaptic growth in the frontal cortex in early development could contribute to individual differences in IC. Huttenlocher's work was based on very small samples, and the time course of these changes could vary greatly across individuals. However, his neuroscience techniques are not appropriate for use with living children.

A noninvasive technique for measuring cortical maturity in developmental populations is electroencephalography (EEG), a continuous recording of the brain's electrical activity detected at the scalp. In general, EEG activity is a summation of postsynaptic potentials generated from multiple groups of cortical neurons firing in synchrony (Davidson, Jackson, & Larson, 2000). The raw signal is composed of multiple sine waves cycling at different frequencies; Fourier analysis decomposes the EEG into these different sine waves and estimates the spectral power in different frequency ranges, which are associated with different kinds of cognitive processes. In adults, power in the 8-12 Hz (alpha) frequency range has been *inversely* associated with underlying cortical activation and strongly implicated in WM and IC (Klimesch, 1999). For example, alpha power values measured over the parieto-occipital cortex (which is involved in visual processing) decrease when subjects are visually attending to the environment but increase when subjects are selectively ignoring information in their visual fields (Klimesch, 2012). Similarly, alpha power values measured over the frontal cortex decrease during states of heightened emotional arousal but increase when subjects are actively manipulating information in WM (Sauseng et al., 2005). Underneath the frontal cortex lies the limbic system, which is involved in emotion and motivation. Thus, the alpha rhythm is thought to be involved in *cortical inhibition*, and frontal alpha activity may be involved in 'top-down' control processes associated with executive function and self-regulation.

Importantly, although neuronal firing rates will change in response to external stimulation, cortical neurons fire spontaneously at rest, and resting (i.e., baseline) EEG power values are thought to reflect the 'excitability' of groups of neurons (Nunez, 1981). Quite often, the resting level of alpha power is positively associated with the degree of event-related change (e.g., Doppelmayr, Klimesch, Pachinger, & Ripper, 1998), which has been observed with other physiological measures (e.g., respiratory sinus arrhythmia). Developmental EEG work has suggested that a 6-9 Hz band is the functional equivalent of the adult alpha band in infants and young children (Stroganova, Orekhova, & Posikera, 1999), and resting frontal EEG power values in this band increase linearly across the first few years of life (Marshall, Bar-Haim, & Fox, 2002). For these reasons, resting frontal alpha activity has been conceptualized as a measure of brain maturation associated with 'WM/IC' capacity (Bell & Fox, 1994).

In the empirical literature, individual differences in resting frontal alpha power have been positively associated with IC skills in infants and young children. For instance, Bell and Fox (1997) reported that 8-month-old infants who succeeded on the A-not-B task had significantly larger frontal alpha power values at baseline than infants who failed the task. Wolfe and Bell (2004) similarly reported a significant positive association between 4.5-year-olds' resting frontal alpha power and their performance on the Day-Night Stroop. In that study, children's frontal alpha power, observed receptive vocabulary and parent-report of temperament (approach/anticipation) accounted for 90% of the variance in their task performance. Importantly, however, these children's performance on the Day-Night task in a subsequent study was not significantly related to their A-not-B task performance in infancy (Wolfe & Bell, 2007). Further, resting frontal alpha power at 8 months was *negatively* associated with resting frontal alpha power at 4.5 years; thus, infants with lower levels of frontal cortical maturity may have exhibited the greatest levels by early childhood. In a different sample, Kraybill and Bell (2013) reported a significant *negative* association between children's resting frontal alpha power at 10 months and their performance on an executive function battery (including the Day-Night task) at 4 years. Thus, it is unclear from previous work if children's rudimentary and verbally-mediated IC skills are related, or how the amount of change in frontal cortical maturity across the toddler years might be associated with children's IC in preschool.

Resting frontal alpha activity may provide an index of frontal cortical maturity associated with WM capacity, which may directly support IC. However, because the nature of WM may undergo dramatic changes across the toddler years as children develop language, it may be useful to consider change in this measure as a predictor of IC. Specifically, if the amount of change in resting frontal alpha power from 1 to 3 years, a period of rapid advances in language, is a significant predictor of IC over and above the resting levels in infancy (i.e., preverbal), it could suggest that verbally-mediated IC skills do not merely develop by building on existing capacities associated with *spatial* WM. Although linear change in children's resting frontal alpha power values have been observed in developmental studies, very little work has investigated individual differences in these changes or how variation in the amount of change is associated with children's emerging IC skills. Thus, the first specific aim of the study was to investigate maturation of the frontal cortex across the toddler years in a community sample, as indexed by developmental change in their resting frontal EEG power values from 10 months to 3 years, and to examine how variation between children in the initial levels and amount of change were associated with variation in their IC at 4 years (see Figure 1).

The Role of Language in the Development of Inhibitory Control

As the frontal lobes are undergoing maturation, and as WM skills are improving, important changes are taking place in the domain of language. Although infants may not need language to inhibit behaviors that are incongruent with their practical knowledge and goals, young children may need language to inhibit behaviors in accordance with rules and societal standards. Indeed, a clear difference between the IC skills of infants and those of young children concerns the role of language in their assessment. For Diamond (1988) this distinction was not important because the underlying ability being measured—the child's use of WM to inhibit behavior—was the same. However, because the nature of WM in the infant and child IC tasks is completely different (visual-spatial vs. auditory-verbal), the underlying processes being measured could be as well. Words may provide children with new ways of internally representing information (e.g., holding rules in mind) and may serve as 'tools' for resolving conflicts among thought and action (Zelazo, 2004). Thus, the acquisition of language may radically change how children think and may support the emergence of new, verbally-mediated IC skills.

In the real world, IC is typically needed in situations that elicit cognitive conflict, or discrepancies in information processing. An infant participating in the A-not-B task likely experiences conflict when they notice that the toy is being hidden in a different location than in the past. Similarly, IC tasks designed for use with young children (e.g., Day-Night, Simon Says, Hand Game) are thought to tap into the kinds of conflicts they experience in the real-world. For example, like the arbitrary rules in those tasks (e.g., make a fist when my hand is flat), in a preschool classroom, children may be expected to follow rules or instructions that conflict with their immediate or otherwise dominant response tendencies (e.g., play with a different toy if a desired one is occupied; refrain from blurting out when another child has been called on). Not only is it impossible to administer rule-based IC tasks to preverbal infants, it makes no theoretical sense to, as they do not encounter situations where they must behave in accordance with rules. Thus, in addition to the verbal nature of their administration, IC tasks designed for use with young children differ from those designed for infants in that they elicit a distinctly different kind of conflict that is associated with language and socialization.

Although it may still rely on WM, by early childhood, IC may also involve the internal use of language. In support of this, subsequent experiments using the Day-Night task revealed that when the demands placed on WM were reduced (e.g., by instructing children to 'say the opposite,' thereby chunking two rules into one), children's performance did not improve (Diamond, Kirkham, & Amso, 2002). However, when children were instructed to respond to the test cards with labels that were not semantically related to one another (e.g., say 'pig' when you see a moon and 'dog' when you see a sun), 4-year-olds performed significantly better than in the standard version of the task. This suggested that one reason young children had difficulty inhibiting behavior in this task was not due to insufficient WM capacity, but because it required them to resolve internal conflicts associated with word meaning. Thus, unlike the rudimentary IC skills of infants, which may involve *detecting* conflict (e.g., noticing when something is different) but that do not involve an adjustment of goals or motivations, by the preschool period, IC may additionally involve *resolving* conflict, and children's use of language may play a role in this process.

According to Soviet theoretical perspectives, it is only with the aid of speech, a uniquely human capacity, that our 'natural' or otherwise dominant associations with stimuli can be modified. To investigate the regulatory function of speech, Luria (1961) conducted experiments with young children involving a rubber bulb connected to a potentiometric recorder. Using a basic 'Go/No-go' paradigm, he instructed children to squeeze the bulb when a red light came on (go) but to *not* squeeze when a blue light came on (no-go). Although older preschoolers did well with this, 3-year-olds had considerable difficulty (they continued to squeeze for the blue light). But, when 3-year-olds accompanied their squeezing with self-directed commands ('Press!') they were better able to inhibit pressing on 'no-go' trials. Apparently, pairing the 'to-be-activated' response with speech changed how children responded to *both* lights: for both stimuli, they may have experienced a 'verbally-mediated pause' associated with speech preparation (*Do I say something for this light?*) that led to greater control over their responding. However, this facilitative effect of speech was observed even when the words were replaced with nonsense syllables ('tu-tu'), suggesting it was the *motorical* act of speaking that was responsible. But, when 3-year-olds were further instructed to accompany their *non*-responses with speech ('*Don't* press!') their performance worsened, whereas 4-year-olds did well. Thus, in addition to verbally pausing, 4-year-olds (but not 3-year-olds) may have been thinking about what the words meant.

Luria's experiment demonstrated that a 'verbal pause' could be interposed between a stimulus and manual response by pairing children's speech with their manual responses to the stimuli; consequentially, their subsequent reactions to those stimuli were more controlled. By 4 years, children could also use the semantic meanings of the words (vs. the motoric aspect of speech) to regulate their behavior. Although this experiment was not designed to elucidate mechanisms of individual differences in IC, it may be possible for children to pair speech with their experiences in the real world in ways that alter how they respond to eliciting events. In the real world, children's need for IC is usually precipitated by an awareness of *conflict* (e.g., being told to follow rules or instructions that conflict with motivation or goals). Thus, the ways in which young children use speech to resolve conflicts in their daily lives (i.e., during problem-solving) may serve an important role in the continued development of IC across the fourth year.

Private Speech and the Development of Inhibitory Control

Luria's experimental work with children stemmed from his earlier collaboration with Vygotsky, who had been observing the spontaneous (i.e., self-generated) private speech of young children as they encountered difficulties and solved problems. A typical experiment was described in his translated work:

> The candy was placed out of reach so the child could not obtain it directly. As the child got more and more involved in trying to obtain the candy, 'egocentric' speech began to manifest itself as part of her active striving. At first, this speech consisted of a description and analysis of the situation, but it gradually took on a 'planful' character, reflecting possible paths to solution of the problem (Vygotsky, 1978, p. 25).

This quotation highlights two important aspects of Vygotsky's theory. First, although private speech was thought to serve a regulatory function 'in-the-moment' by directing children's attention and behavior in accordance with goals, this behavior was also thought to have a developmental significance. Specifically, young children who spontaneously produced private speech *during* their activity were thought to eventually progress towards speaking *before* their activity; over time, their overt (i.e., fully audible) private speech was thought to become internalized as 'inner speech.' In this way, private speech produced during problem-solving contributed to the bifurcation, or psychological separation, of action planning and action execution. Second, Vygotsky noticed that the amount of private speech increased as a function of task difficulty, a finding that has been observed in multiple studies (e.g., Behrend, Rosengren, & Perlmutter, 1989). Thus, the behavior was occurring naturally in the same contexts where children would ultimately need to use language internally. So, like the children in Luria's experiment who learned to pause and reflect in response to stimuli previously paired with their own speech, young children who regularly speak to themselves during problem-solving may eventually have greater access to inner speech when problems are encountered or when inhibitory demands are placed on their behavior (Vygotsky & Luria, 1994).

For children's private speech to become internalized as inner speech that supports voluntary, *self*-control of action, it may need to be semantically related to their activity, goals, or internal experiences; they may need to be talking about themselves as objects or what they are trying to do (e.g., describing activity, planning, asking questions). A child who routinely asks themselves goal-relevant questions when challenged (e.g., *Where should I take this?*), for instance, may develop a tendency to pause and consciously reflect in challenging situations. In contrast, private speech that is largely self-stimulating (e.g., making sounds, repeating words/phrases), task-irrelevant, or that occurs only in response to events (e.g., affective exclamations) could represent a kind of impulsive motor behavior that reinforces impulsive action in similar contexts over time. Thus, young children who produce large amounts of private speech during problem-solving could be at greater risk for having problems with IC than other children. But, the maturity of their private speech (i.e., the proportion of their private speech that is mature) could be positively associated with IC.

In line with this idea, school-aged boys diagnosed with ADHD (a disorder characterized by deficits in IC) have produced significantly greater amounts of private speech during problem-solving than other children (Berk & Potts, 1991; Winsler, 1998). Subsequent research revealed that these group differences also were present at younger ages. Specifically, Winsler and his colleagues (2000) reported that a group of preschoolers 'at risk' for ADHD (based on teacher-report of behavior problems in the classroom) produced a significantly greater amount of private speech during a challenging puzzle task at 3.5 years than children not reported as difficult to manage. That they produced a greater amount of immature private speech (e.g., making sounds, repeating syllables), mature private speech (e.g., asking task-relevant questions, describing activity), and social speech (to the experimenter) than controls suggests that children who are characteristically impulsive and distractible may talk more than other children in problem-solving contexts, possibly as part of a strategy to gain mastery of their behavior (Berk & Winsler, 1995).

Importantly, in the Winsler et al. (2000) study, the amount of mature private speech children produced during problem-solving at later timepoints was significantly negatively associated with their IC task performance and positively associated with teacher-report of attention and behavior problems. Thus, producing a greater *amount* of mature private speech may not promote the development of IC in the preschool period. However, in a subsequent study with 3- and 4-year-olds, the relative maturity of children’s private speech during problem-solving was positively associated with indices of their self-regulation in the classroom (Winsler, de León, Wallace, Carlton, & Willson-Quaye, 2003). Specifically, controlling for age, the proportion of children’s private speech that was task-irrelevant (i.e., immature) was significantly negatively correlated with their teacher-reported social skills and positively correlated with their externalizing problems. In contrast, the proportion that was partially-internalized (i.e., task-focused muttering) was positively correlated with social skills and negatively correlated with externalizing. The proportion that was overt (i.e., fully audible) and task-relevant was also negatively correlated with social skills but was not significantly related to externalizing. Thus, although the overall amount of private speech young children produce during problem-solving may indicate their risk for having problems with IC, the maturity of their private speech may influence the development of their IC skills.

Despite an extensive body of research on the role of children’s private speech in the development of self-regulation (Winsler, 2009), the role of children’s social speech in this process is unclear. Vygotsky (1987) thought that mature forms of private speech (e.g., asking oneself task-relevant questions) originated from children’s verbal exchanges with adults during problem-solving. In his experiments, he noticed children would often alternate back and forth between appealing to an experimenter for help and talking themselves though the problem. Thus, theoretically, a certain amount of ‘help-seeking’ social speech during problem-solving may be important for children’s emerging IC skills. However, because it may be important for children to eventually turn this speech towards themselves, it is unclear whether it would be positively or negatively related to IC in the preschool period. Further, it is unclear whether the speech children direct towards an experimenter in these contexts is a meaningful index of their tendency to rely on social speech during problem-solving in the real world, which may largely involve caregivers. Most empirical work on this topic has observed children's private speech from highly-structured problem-solving tasks administered by an experimenter; few studies have examined children's private *and* social speech during problem-solving in a context where their speech could be directed towards caregivers.

Collectively, this work suggests that young children's problem-solving speech may play an important role in the continued development of IC across the fourth year. First, the overall amount of speech young children produce in challenging contexts may indicate their overall risk for having problems with IC, but the maturity of their private speech at 3 years may help explain additional variance in their IC at 4 years. Additionally, because mature forms of private speech may originate from socialized language, the proportion of 3-year-olds social speech that is help-seeking could also be positively associated with their IC at 4 years. Although some studies have examined children's speech during problem-solving longitudinally in the preschool period, the longitudinal associations between these different aspects of speech and IC were not examined. Thus, <u>a second aim of the current study was to observe children's speech at 3 years from a naturalistic problem-solving context and to examine the amount and content of their private and social speech as predictors of their IC at age 4 (see Figure 1).</u>

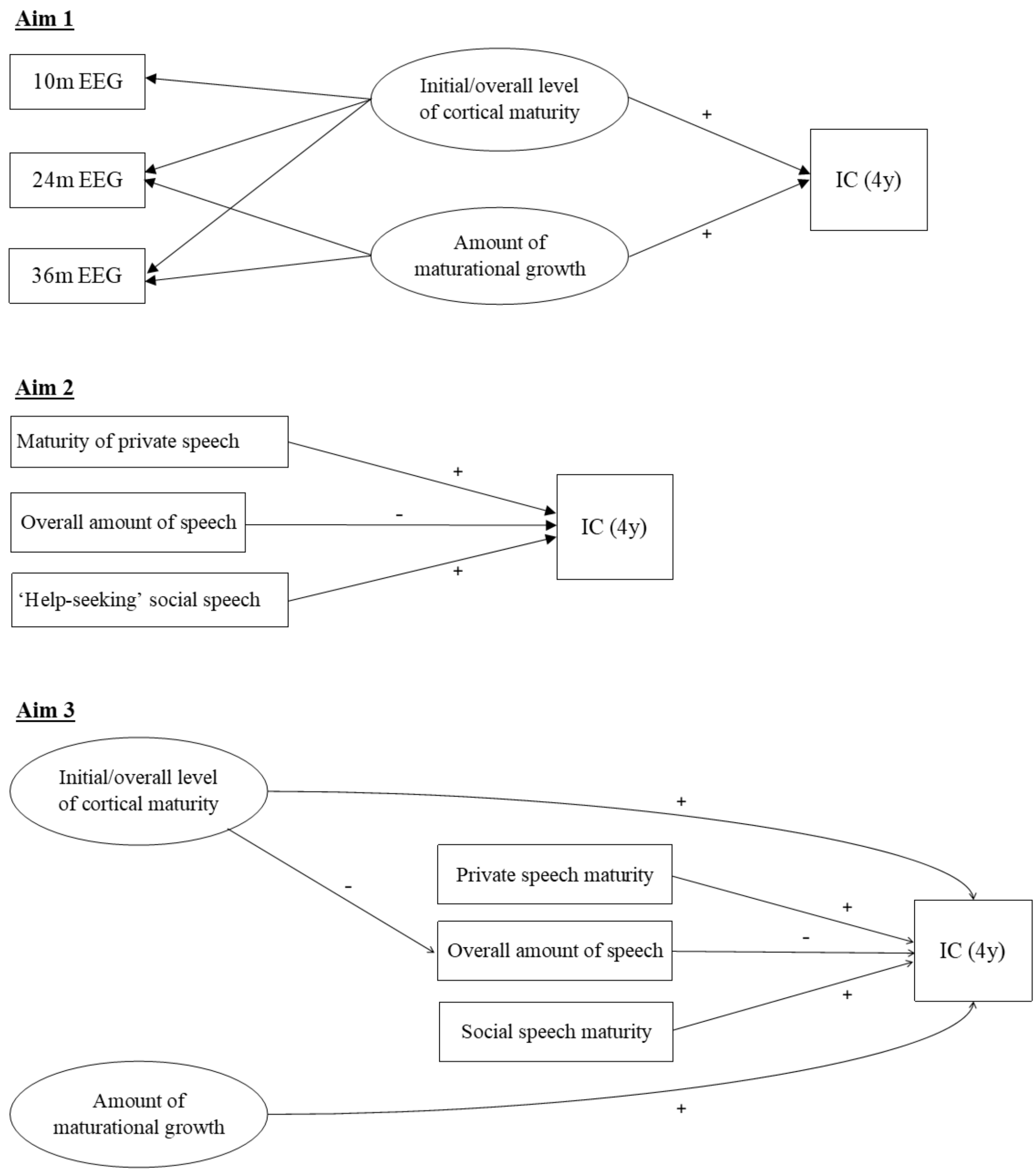
Frontal Cortex Maturation and Speech during Problem-Solving

In addition to its importance for higher-order cognitive processes (e.g., WM), the frontal cortex is also thought to be important for language (Alexander, Benson, & Fuster, 1989). Regions of the left frontal cortex (e.g., Broca's area), for instance, are thought to be uniquely specialized for speech. Further, the developmental time course of frontal cortex maturation and that of expressive language are overlapping: most infants produce their first word around 1 year of age, when synaptic density in the frontal cortex first exceeds adult levels, and children's vocabulary increases exponentially across the toddler years. Thus, in addition to its influence on WM, maturation of the frontal cortex could be associated with aspects of language development that influence the amount or maturity of children's speech during problem-solving. As such, both direct and indirect associations between the overall level of frontal cortical maturity and/or the amount of frontal cortical maturation across the toddler years and IC in preschool are possible.

One reason children's frontal cortical maturity may be associated with the amount of speech they produce during problem-solving is because of the brain's hierarchical organization. The limbic system, a collection of structures that are important for memory, emotion, and motivation, lies directly beneath the frontal cortex. When young children are faced with problems and challenges, there is likely to be activation of the limbic system; upward (i.e., 'bottom-up') projections from the limbic system to the frontal cortex may play an essential role in expressive language, and speech during problem-solving in particular. However, as the frontal cortex matures, in addition to an increasing capacity for WM, there may be an increasing amount of cortical inhibition being exerted over lower-level neural systems (e.g., limbic; Lewis, 2005). Consequentially, young children may produce more speech during problem-solving when their frontal cortices are relatively less mature.

No studies have reported on the associations between frontal cortical maturity and speech during problem-solving in children. However, recent neuroimaging work suggests that children with ADHD (who may produce a greater amount of speech during problem-solving than other children), have delays in frontal cortical maturation (Shaw et al., 2007). Additionally, in infants, higher-order cognitive processes (e.g., WM) and expressive communication behaviors have shown opposite relations with resting frontal EEG power in the alpha band. Specifically, in contrast to Bell and Fox (1997), who reported a significant positive association from infants' resting frontal alpha power and their performance on an experimental task of IC, in a different study, the relation between infants' resting frontal alpha power and their communicative gesturing (pointing) was negative (Henderson, Yoder, Yale, & McDuffie, 2002). Similarly, in other developmental studies, decreases in central alpha power during the observation of others' actions have been attributed to the activity of mirror neurons that support cognitive processes underlying imitation (e.g., self-other mapping; Marshall, Saby, & Meltzoff, 2013). Thus, although children with less mature frontal cortices may have a lower capacity for WM, they may be more likely to express themselves communicatively, especially in problem-solving contexts (when the limbic system would be activated). Thus, a final aim of the study was to examine the indirect associations between the overall level of children's frontal cortical maturity across the toddler years and their IC at 4 years through the amount and maturity of speech they produced during problem-solving at 3 years. A set of models depicting study aims and hypotheses can be seen in Figure 1.

Figure 1. Models Depicting Study Aims and Hypotheses



CHAPTER II

CURRENT STUDY

IC in the preschool period is particularly important for children's well-being (e.g., Allan, Hume, Allan, Farrington, & Lonigan, 2014; Perry et al., 2017). However, a comprehensive understanding of the factors that may account for individual differences in preschoolers' IC is lacking. Individual differences in self-regulation are thought to have a biological basis (Calkins, 2007). Biologically, IC may depend on WM resources associated with the frontal cortex, which undergoes considerable maturation across the first few years of life; variation between children in the amount of growth could contribute to individual differences in their IC (Diamond, 2002). However, in addition to WM, by early childhood IC may also involve the internal use of language, and children's use of language (i.e., speech) in challenging contexts may further contribute to individual differences in IC by influencing this emerging ability (Vygotsky & Luria, 1994). Although these biological and behavioral factors (frontal cortical maturity and speech during problem-solving) have been examined in relation to children's IC in previous work, no study has examined their longitudinal associations with IC in the same model or their associations with one another. Thus, the current study aimed to investigate the longitudinal associations among maturational growth in the frontal cortex across the toddler years, speech during problem-solving at 3 years, and IC at 4 years in a community sample of typically-developing children.

The study consisted of six research questions: 1) Is there a significant amount of change in children's frontal cortical maturity, as indexed by resting levels of frontal EEG power in the 'developmental alpha' band, from 10 months to 3 years? 2) Is variation between children in the initial levels and amount of change in frontal cortical maturity from 10 months to 3 years significantly associated with variation in their IC at 4 years? 3) Is the amount and maturity of children's private speech during problem-solving at 3 years significantly associated with their IC at 4 years? 4) Is children's social speech during problem-solving also significantly associated with their IC at 4 years? 5) Is variation between children in the overall level of frontal cortical maturity from 10 months to 3 years significantly associated with variation in the amount of speech they produce during problem-solving at 3 years? 6) Is variation between children in the overall level of frontal cortical maturity from 10 months to 3 years significantly indirectly associated with their IC at 4 years through an influence on the amount of speech they produce during problem-solving at 3 years? Study aims and hypotheses are described in detail below.

Study Aim 1

The first specific aim was to investigate maturational growth in the frontal cortex across the toddler years, and to examine how variation between children in the initial level of frontal cortical maturity and amount of change during this time were associated with variation in their IC at 4 years. Neuroimaging work suggested that synaptic density in the human frontal cortex exceeds adult levels by the end of the first year and reaches peak levels between 2 and 4 years (Huttenlocher, 1979; Huttenlocher & Dabholkar, 1997), when rapid improvements in IC have been observed. Diamond (1988, 2002) hypothesized that maturational growth in the frontal cortex was partially responsible for the age-related improvements in children's IC skills. However, few studies have investigated the maturational changes taking place in this part of the brain across infancy and early childhood or how individual variation in those changes (e.g., amount of growth across the toddler years) may be associated with variation in preschoolers' IC skills.

EEG is a noninvasive method for measuring cortical maturity in developmental populations. Specifically, EEG activity in the 'alpha' frequency range is thought to reflect neural activity associated with WM and cortical inhibition. The resting amplitude of this rhythm at frontal scalp sites may provide an index of frontal cortical maturity associated with WM/IC capacity (Bell & Fox, 1994). Consistent with earlier neuroimaging work, developmental EEG studies have reported mean increases in children's resting frontal alpha power from 10 months to 4 years (Marshall et al., 2002). However, in a cross-sectional study with children aged 3.5, 4, and 4.5 years, the youngest group of children exhibited the largest resting frontal alpha power values (Wolfe & Bell, 2007). Thus, age-related increases in resting frontal alpha power may provide an index of frontal cortical maturation associated with the increasing availability of WM resources, but by 4 years many children may have entered a synaptic pruning phase in the frontal cortex.

Theoretical work beyond the scope of this study has highlighted the fourth year of life as an important time in children's brain development. Specifically, neural networks in the frontal cortex associated with effortful self-regulation are thought to be rapidly forming during this time (Rothbart, Sheese, Rueda, & Posner, 2011). Thus, examining developmental EEG changes across the fourth year in relation to children's IC at 4 years is important. However, prior to exploring those associations, it may be meaningful to first explore how maturational brain growth in the frontal cortex prior to age 3 is associated with children's IC at age 4. Further, to effectively address the first research question, it is important to examine change in children's resting frontal EEG power values during a time when these values are expected to increase on average. Thus, in the current study, a significant amount of positive change in children's resting frontal alpha power values from 10 months to 3 years was expected.

If age-related increases in the resting amplitude of the frontal alpha rhythm are the result of brain maturational process, then per Diamond's theory, variation between children in the overall level or amount of change across the toddler years should be associated with variation in their IC skills in preschool. Individual differences in resting frontal alpha power values were positively associated with IC skills in infants and young children concurrently (Bell & Fox, 1997; Wolfe & Bell, 2004). However, the longitudinal associations between resting frontal alpha power in infancy and IC in early childhood were negative (Kraybill & Bell, 2012), and infants who achieved success on Piaget's A-not-B task did not necessarily perform well on the Day-Night task as preschoolers (Bell & Wolfe, 2007). No study has simultaneously examined whether the initial levels and amount of change in resting frontal alpha power from infancy to early childhood are associated with IC in preschool. If preschoolers' IC skills build on existing capacities that emerge in infancy associated with spatial WM, then a positive association between resting frontal alpha power in infancy and IC at age 4 would be expected. However, because the toddler years (e.g., 10 to 36 months) are a time of rapid advances in language, maturational growth in the frontal cortex during this time could more closely index the amount of frontal cortical resources that are specialized for verbal (vs. spatial) WM. Thus, in the current study, significant positive associations between the initial levels and amount of change in resting frontal alpha power from 10 months to 3 years and IC at 4 years were expected.

Study Aim 2

In contrast to rudimentary forms of IC that emerge in infancy, verbally-mediated IC skills (i.e., inhibiting behavior according to rules or instructions) are thought to be more complex in that they additionally involve using language internally. Children's ability to use language internally to control behavior appropriately may develop as a consequence of using language in challenging contexts. Thus, a second aim of the study was to observe children's speech during problem-solving at 3 years and to examine the overall amount and content of their private and social speech as predictors of their IC at age 4. Most theoretical and empirical work has focused on children's private speech. Vygotsky's (1962) original observations and early cross-sectional research on private speech in children suggested that it followed a curvilinear time course: overt self-talk was observed maximally in the early preschool years but became less frequent and more internalized (e.g., muttering) by elementary school (Berk & Winsler, 1995). Considering the improvements in IC that have been observed across the fourth year, children's private speech during problem-solving at 3 years may play an important role in this developmental process. However, the role of children's social speech is unclear.

Theoretically, for children's private speech during problem-solving to support the development of IC it may need to be meaningfully related to their activity, goals, or feelings. Specifically, when this kind of 'mature' self-directed speech is repeatedly paired with children's experiences of conflict and challenge, they may develop a tendency to pause and think themselves through problems instead of impulsively responding. In contrast, private speech that is self-stimulating (e.g., repeating words or phrases, making sounds), semantically irrelevant to the task at hand, or that occurs only in response to events (e.g., affective exclamations) may represent impulsive motor behavior, and could serve to promote impulsive action in response to conflict over time. Berk (1986) developed a coding scheme for distinguishing between self-directed utterances that were task-relevant and self-guiding (e.g., describing activity, planning) from those which were primarily self-stimulating (e.g., singing, repeating sounds or phrases) or irrelevant to the task at hand. Interestingly, studies have found that preschoolers with lower IC produce a greater amount of speech during problem-solving in general, and negative associations between the *amount* of mature private speech children produced and their self-regulation abilities have been reported (Winsler et al., 2000). However, in one study, the *proportion* of preschoolers' private speech that was mature was positively associated with their IC (Winsler et al., 2003). Thus, young children who produce a greater amount of speech during problem-solving may have lower IC in the preschool period, but the maturity of their private speech at 3 years may contribute to variation in their IC at 4 years.

Because young children may typically solve problems within a social context, characteristics of their social speech during problem-solving may also contribute to variation in their IC. Although few studies have reported on children's social speech during problem-solving, there is some indication form previous work that it is important to consider. First, young children at-risk for having problems with IC, in addition to producing a greater amount of private speech during problem-solving, also produced a greater amount of social speech than other children (Winsler et al., 2000). Additionally, in a different study, the proportion of preschoolers' total speech during problem-solving that was private was positively associated with their sustained attention in the classroom (Winsler et al., 2003). Thus, a greater amount of social speech during problem-solving may not be positively associated with self-regulation skills in the preschool period. However, in those studies, the content of children's social speech (i.e., whether it was on-task/instrumental vs. off-task/irrelevant) was not reported, nor were its associations with their IC. Because theoretically, mature forms of private speech may originate from 'help-seeking' social speech (i.e., children ask adults for help then turn that speech towards themselves), a greater proportion of social speech during problem-solving at 3 years that is devoted to seeking help may be positively associated with IC at 4 years.

Based on theory and previous research, in the current study, the overall amount of speech children produced during problem-solving at 3 years was expected to be negatively associated with their IC at 4 years whereas the proportion of their private speech that was 'mature' and the proportion of their social speech that was 'help-seeking' were expected to be positively associated. Observing this speech at 3 years was important because this is when children's private speech is thought to be maximal and when their verbally-mediated IC skills are not yet reliably observable. Additionally, observing this speech from a challenging context was important because it is by pairing speech with their experiences of *conflict* that children's private speech is thought to influence their emerging IC skills. A common method of observing private speech in young children has involved providing them with difficult or challenging puzzles, and studies have found that the amount of private speech increases with the level of puzzle difficulty (Behrend et al., 1989). Thus, to effectively elicit private speech in 3-year-olds it is crucial to provide a puzzle that is sufficiently difficult but not too far beyond their developmental level. Finally, observing this speech from a challenging context in which children had the opportunity to address caregivers was important, because this arrangement may more closely match up with the contexts in which they experience challenges in the real world.

Study Aim 3

The final aim of the study was to examine whether the amount of speech children produced during problem-solving at 3 years was a mediating mechanism linking the overall level of frontal cortical maturity across the toddler years to IC at 4 years. Very few studies have examined the associations between frontal cortical maturity and speech behavior in children. However, because speech is thought to involve the frontal cortex, variation in the overall level of frontal cortical maturity across the toddler years or the amount of change during this time could contribute to individual differences in the amount or maturity of children's speech during problem-solving at 3 years. During problem-solving there may be activation of the limbic system, which lies directly beneath the frontal cortex. 'Bottom-up' signals from the limbic system to the frontal cortex in response to challenges could promote the production of speech during problem-solving.

Because frontal cortical maturity is associated with cortical inhibition (i.e., suppression of 'bottom-up' signals from lower-level neural systems), children with lower overall levels of frontal cortical maturity across the toddler years may produce the greatest amount of speech during problem-solving at 3 years. Additionally, because a greater amount of speech during problem-solving has been negatively associated with IC in previous work, in the current study, <u>a significant positive indirect effect from the overall level of resting frontal EEG alpha power to IC through the amount of speech during problem-solving was expected</u>.

CHAPTER III

METHODS

Sample

The current study used data from a cohort of children who participated in a longitudinal study investigating the role of psychobiological processes in cognitive and emotional development. The full sample (N = 410) was recruited at two research locations (Blacksburg, Virginia; Greensboro, North Carolina) via commercial flyers and mailing lists generated from county birth records; 49% were male, 73% were racially White and non-Hispanic, and 71% had ≥ 1 parent with a 4-year college degree. Due to availability of DVDs for coding, only children from the Greensboro site (N = 199) were considered for inclusion in the study; this cohort was more diverse in terms of race, ethnicity, and parental education compared to the full sample (53% were male, 59% were racially White and non-Hispanic, and 63% had ≥ 1 parent with a 4-year college degree). Children from this cohort with any usable data were included in the study.

The reduced sample (N = 180) was similar to the full cohort in terms of demographic characteristics: 54% were male, 61% were racially White and non-Hispanic, and 67% had ≥1 parent with a 4-year college degree. One-hundred and seventy-two infants came into the lab at 10 months (M = 10.26, SD = .32); 165 toddlers came into the lab at age 2 (M = 24.58, SD = .70); 157 children came into the lab at age 3 (M = 36.72, SD = .92); and 162 participated (145 came into the lab) at age 4 (M = 48.70, SD = .92).

Procedure

Upon arrival to the laboratory at each visit, families were greeted by a research assistant who explained the study procedures and obtained signed consent. After an initial warm-up period, children were fitted with EEG caps and baseline physiology was collected. Subsequently, at the 2-, 3-, and 4-year visits, children participated in a battery of experimental tasks designed to assess IC while mothers completed questionnaires; afterwards, EEG caps were removed, and a series of tasks designed to assess children's self-regulation abilities were administered. Families were compensated $50 for each visit. A summary of measures included in the study are displayed in Table 1.

Measures

Electroencephalography (EEG). Children's frontal cortical maturity was estimated from resting-state EEG (power) in the 6-9 Hz 'developmental alpha' band. Baseline EEG was recorded at each lab visit while children watched a brief video clip, a procedure commonly used with infants and young children because it limits gross motor movements (Bell & Cuevas, 2012). At the 10-month visit, infants were seated in a high-chair and shown a brief (M = 46 s) clip from *Sesame Street* (Cecile, Up Down, In Out, Over Under). At the 2- and 3-year lab visits, children were seated at a small table and shown a clip from the Disney film *Finding Nemo* (Sea Turtles Riding the Eastern Australian Current; M_2 = 65 s; M_3 = 118 s). Mothers were seated nearby but instructed not to interact with their child. Among children who came into the lab, EEG data at 10 months was missing for 6 participants (1 refused the cap, 1 had too much movement artifact, 4 were excluded due to signal abnormalities); EEG data at 2 years was missing for 14 participants (10 refused the cap, 4 were excluded due to signal abnormalities); EEG data at 3 years was missing for 16 participants (10 refused the cap, 6 were lost due to equipment failure/technical errors).

Calibration. Prior to the recording of each subject, the bioamplifiers were calibrated to ensure that EEG data were not affected by transient electrical noise that could be different across subjects. Specifically, a 10-Hz, 50-uV peak-to-peak sine wave was input through the amplifier, digitized for 30s, and stored for subsequent analysis.

Data collection. Upon each arrival to the research laboratory, children were fitted with lycra stretch EEG caps (Electro-Cap, Eaton, OH) with electrodes in the 10/20 system pattern (Jasper, 1958; Pizzagalli, 2007). After the cap was placed on the child's head, recommended procedures regarding EEG data collection with infants were followed (Bell & Cuevas, 2012). Specifically, a small amount of abrasive gel was placed into each recording site and the scalp was gently rubbed; conductive gel was then placed into each site with a syringe. Electrode impedances were measured and accepted if they were below 10K ohms. Recordings were made from 16 left and right scalp sites: frontal pole (Fp1, Fp2), medial frontal (F3, F4), lateral frontal (F7, F8), central (C3, C4), temporal (T7, T8), medial parietal (P3, P4), lateral parietal (P7, P8), and occipital (O1, O2). All electrode sites were referenced to Cz during recording. The electrical activity from each lead was amplified using James Long Company Bioamps (Caroga Lake, NY). During data collection, activity for each lead was displayed on an acquisition computer monitor using Snapshot-Snapstream software (HEM Data Corp., Southfield, MI). The

EEG signal was digitized online at 512 samples per second for each channel so that the data were not affected by aliasing. Raw data were stored for later analyses.

Data processing. EEG data were subsequently examined and analyzed using EEG Analysis System software developed by the James Long Company (Caroga Lake, NY). First, spectral analysis of the calibration signal and computation of power at the 9- to 11-Hz frequency band was accomplished; these power figures were used to calibrate the power derived from the EEG recordings. Next, the calibrated EEG data were band-pass filtered to eliminate electrical activity that was outside the frequency range of human brain activity (.5 - 45 Hz), which can interfere with artifact scoring. Second, the filtered data were re-referenced to an average reference configuration, which essentially weighted all the electrode sites equally and eliminated the need for a non-cephalic reference (Lehmann, 1987). Active (e.g., F3) to reference (Cz) electrode distances vary across the scalp; without the re-referencing, power values at each active site may reflect inter-electrode distance as much as they reflect electrical potential. Third, the re-referenced EEG data were manually artifact scored for eyeblinks (which are prominently observable in Fp1/Fp2) and gross motor movements; these artifact-scored epochs were eliminated from all subsequent analyses. Last, the artifact-scored EEG data were analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1-s width and 50% overlap and spectral power at each electrode site was computed for the 6- to 9-Hz frequency band. Power was expressed as mean square microvolts and the data were transformed using the natural log (ln) to normalize the distribution.

Inhibitory Control. Children's IC was observed at 4 years from their performance on a battery of tasks that required inhibition of a dominant behavioral response, and from adults' reports of their behavior (4 experimental tasks; 3 questionnaire measures).

Experimental tasks. In the Simon Says task (Hughes, 1998), children were instructed to obey the commands given by one hand puppet (e.g., *Touch your nose!*) but to ignore the commands given by another puppet. Approximately 4 'go' and 4 'no-go' trials were administered in an alternating order. A trained coder later scored the task by watching the DVD recording; points were awarded when the child touched the appropriate body part on 'go' trials and when they did not touch their bodies on 'no-go' trials. The proportion of correct 'no-go' trials was calculated and used in the analyses. Reliability scoring for this task was accomplished by the primary site on 16% of the sample and was within acceptable range (ICC = .99). Among children who came into the lab at age 4, data for this task was missing for an additional 9 children (5 refused to play, 3 were unable to understand the task rules, and 1 was voided due to errors in administration).

In the Day-Night task (Gerstadt et al., 1994), children were instructed to say 'day' when shown a black card with a picture of a yellow moon and to say 'night' when shown a white card with a picture of a yellow sun. Children were given a minimum of two practice trials followed by 16 test trials (8 with the sun card and 8 with the moon card arranged in a pseudorandom order). A trained coder (the author) later scored the task by watching the DVD recording; points were awarded when the child responded to the cards with the opposite labels. The percentage of correct trials was calculated, and from these proportional scores, reliability was accomplished by the primary site on 13% of the sample (ICC = .96). However, consistent with previous studies (e.g., Gerstadt et al., 1994), some children exhibited response patterns that resulted in 'false positive' trials (18 children simply *alternated* saying 'day' and 'night' in a mindless fashion; 6 children *perseverated* by saying the same word for each trial). Because these response patterns resulted in some correct trials that were due to chance alone, for these 24 participants, 'false positive' correct trials were subtracted from the total number of correct trials. The proportion of valid correct trials was calculated and used in the analyses. Data for this task were missing for an additional 25 children (13 refused to play, 11 could not understand the task rules, and 1 child was too fussy/emotionally distressed).

In the Three Pegs task (Balamore & Wozniak, 1984), children were given a wooden mallet and instructed to tap a set of colored pegs in non-canonical order; to succeed, they needed to inhibit the dominant tendency to tap the pegs in the order they were presented (i.e., from left to right). First, a pretest was given to ensure that children could distinguish between the colors (blue, green, yellow). Then, a series of trials were administered; to pass, children needed to tap the correct color sequence twice in a row. If the child tapped correctly, a second trial was conducted. Children received at least two and as many as six trials depending on their pattern of responding. A trained coder (the author) later scored the task by watching the DVD recording and an ordinal score from 0 to 3 was administered. Specifically, children were given a 0 if they failed the task, 1 if they required two repeated instructions, 2 if they required one additional instruction, and

3 if they performed the task after the first demonstration (2 trials). A proportional score (total correct/total trials) was calculated and used in the analyses; this score preserves the rank-ordering of qualitative scores while further differentiating between children assigned the same qualitative score. Data for this task were missing for an additional 3 children (1 could not distinguish between the peg colors, 1 was voided due to errors in administration, and 1 child was too fussy/emotionally distressed).

In Luria's Hand Game (Luria, Pribram, & Homskaya, 1964), an experimenter made one of two hand gestures (fist or flat) and instructed children to respond with the opposite gesture across a series of trials. Specifically, children were asked to place a flattened hand on the table whenever the researcher presented her fist and to present a fist whenever the researcher placed her flattened hand on the table. Children were given at least two practice trials during which they were praised or corrected, and then 16 test trials were administered (8 with the experimenter's fist as the stimulus, and 8 with the experimenter's flattened hand as a stimulus, arranged in a fixed pseudorandom order). A trained coder (the author) later scored the task by watching the DVD recording. A point was awarded when the child responded to the experimenter's hand gesture with the opposite gesture; only the initial response was scored. The percentage of correct trials was calculated for use in the analyses. Reliability scoring for this task was accomplished by the primary site on 14% of the sample and was within acceptable range (ICC = .94). Data for this task were missing for an additional 25 children (6 refused to play, 10 could not understand the task rules, 1 was voided due to errors in administration, and 8 children were too fussy/emotionally distressed).

Questionnaire measures. Mothers reported on their child's IC by completing the Children's Behavior Questionnaire (CBQ; Rothbart, Ahadi, Hershey, & Fisher, 2001), a survey designed to assess general patterns of behavior associated with temperament in children of 3–7 years of age. The shortened form of the CBQ consists of 94 items that load onto 15 scales (Putnam & Rothbart, 2006). The IC scale consists of 6 items that assess children's capacity to plan and to suppress inappropriate approach responses under instructions or in novel or uncertain situations (e.g., *Can easily stop an activity when told no*). For each question, mothers indicated how accurately each item described their child's behavior (1 = extremely untrue, 7 = extremely true) during the 2 weeks prior to the laboratory visit. The IC scale has an internal consistency of .61 in the current sample. Twenty children were missing data for this measure due to nonparticipation.

Mothers reported on their child's behavior problems associated with inhibition using the Behavior Rating Inventory of Executive Functioning (BRIEF-P; Gioia, Espy, & Isquith, 2003), a survey designed to assess problems with executive functioning in preschool children. The BRIEF-P contains 63 items that load onto five scales (Inhibit, Shift, Emotional Control, Working Memory, and Plan/Organize), which showed good internal consistencies in pilot studies (α = .80 - .95; Isquith, Gioia, & Espy, 2004). The Inhibit scale (reflecting *problems* with IC) consists of 16 items (e.g., *Is unaware of how his/her behavior affects or bothers others; Is impulsive; Has trouble putting the brakes on his/her actions after being asked*) and has good internal consistency (Cronbach's alpha = .90) in the current sample. Twenty children were missing data for this measure due to nonparticipation.

Experimenters reported on children's IC by completing the Preschool Self-Regulation Assessment (PSRA; Smith-Donald, Raver, Hayes, & Richardson, 2007), a survey designed to assess self-regulation in emotional, attentional, and behavioral domains from structured laboratory tasks. The PSRA contains 25 items that load onto two broad factors (Attention/Impulse Control, Positive Emotion), which had good internal consistencies (Cronbach's alpha = .87, .89) and interrater reliabilities (ICC = .82, .83) in pilot studies (Smith-Donald et al., 2007). For each item, raters circle the number (0 - 3) that best describes the child's behavior during the laboratory session. The Attention/Impulse Control factor consists of 11 items (e.g., *Child has difficulty waiting between tasks; Thinks and plans before beginning each task; Lets examiner finish before starting task; does not interrupt*) and has an internal consistency of .91 in the current sample. Completion of the PSRA was accomplished by the experimenter who interacted with the child and within 30 minutes of the family leaving. Of the 145 children who came into the lab at age 4, only 1 child was missing data for this measure (the experimenter did not complete the survey).

Problem-Solving Speech. Children's speech was observed at 3 years from a challenging puzzle task. After completing a non-challenging puzzle with their mothers, children were given an alphabet puzzle (*Melissa & Doug*) to complete on their own; mothers were nearby but given an *Oprah* magazine and instructed not to interact with their child. The experimenter took all the pieces (letters) out of the puzzle before leaving the room for 2 minutes (M = 110 s; SD = 26 s). No child successfully completed the puzzle on their own. Due to errors in training, 33 children (21%) were given less than 2 minutes (M = 63 s) to work on the puzzle and were not left alone with their mothers (the experimenter did not leave). Of the 157 children who came into the lab at age 3, only two were missing all speech data (1 could not be coded due to a recording error and 1 was voided due to errors in task administration).

Transcribing utterances. Speech from the puzzle task was transcribed and coded by the author and a research assistant according to established guidelines (Winsler, Fernyhough, McClaren, & Way, 2005). First, a transcript was created for each participant by watching the DVD recording of the task; utterances were entered directly into an Excel file. Utterances were operationally defined as a sentence, sentence fragment, clause, or any string of speech that is separated from another by at least 3 seconds (Winsler et al., 2005). An utterance is conceptually understood as the most basic unit of word meaning, or the smallest piece of speech that can stand alone. An utterance could not contain any temporal or semantic discontinuities, meaning that it could not contain 3 seconds of silence and could not contain a major shift in semantic content. Accuracy of speech transcription was accomplished on 20% of the sample by a trained reliability coder. Of these 31 transcripts, three were flagged as containing potential errors (e.g., one utterance misidentified as two, a soft-spoken utterance was omitted); these videos were watched again and the transcripts were adjusted when necessary.

Speech coding scheme. Coding of speech involved (1) classifying transcribed utterances as social or self-directed and (2) further classifying utterances based on functional content. Utterances were classified as social if they were accompanied by eye contact or gestures, or if they contained a vocative or pronoun reference (Winsler et al., 2005). Utterances that occurred within 2-3 seconds of any previous social utterance (i.e., temporal contiguity) were considered social if they were not also accompanied by a significant change in tone or content. To be consistent with previous research on private speech, self-directed utterances were coded (as much as possible) according to Berk's (1986) scheme, which categorizes children's private utterances based on their overtness (audibility) and task-relevance. This scheme consists of three broad categories: Level 1 (self-stimulating, task-irrelevant private speech) includes word play and repetition, affective exclamations, comments to imaginary others, and other utterances that are semantically unrelated to the task; Level 2 (overt, task-relevant private speech) includes statements or questions about the task, descriptions of ongoing or future task-related activity, and task-relevant affect expression (i.e., verbalization of feelings); Level 3 (partially-internalized) includes inaudible muttering, whispers, and silent lip movements.

Using Berk's (1986) scheme and the Winsler et al. (2005) coding manual as a guide, self-directed utterances were classified into one of 13 mutually-exclusive categories (see Table 2a). First, utterances that could not be transcribed due to poor articulation but that were spoken at full-volume were classified as (1) unintelligible (which Winsler et al. 2005 conceptualized as 'Level 0'). Utterances that could not be transcribed due to low-volume or inaudibility, but that occurred in the context of focused attention and/or task-relevant activity (e.g., putting pieces on) were coded as (13) 'inaudible muttering' (Level 3). Self-directed utterances that were fully audible and intelligible were classified into one of the remaining 11 categories: (2) nonword sounds (e.g., clucking; *bing-bing-bing*); (3) exclamations/transitions (e.g., *Uh-oh!, Well…,* *Um…*); (4) wordplay/repetition (i.e., repeating words or phrases for the sake of saying them; e.g., *B-B-B-B*); (5) fantasy/imaginary dialogue (i.e., talking to the puzzle or speaking *for* the puzzle pieces); (6) task-irrelevant comments or questions (e.g., *Do we eat grapes?; I got football);* (7) 'describing materials' (i.e., talking about the puzzle pieces or clues; e.g., *That's [points] a moon*); (8) speech-action coordination (i.e., words or labels that occurred in conjunction with task-relevant actions; e.g., *This goes here* [puts piece on]); (9) self-correction/feedback (i.e., evaluative statements that followed task-relevant actions; e.g., [tries piece]—*Nope; [puts piece on] That is there.*); (10) planning/describing activity (e.g., *I'm looking for a 'S'; I wanna' put them back in their places; I do this puzzle*); (11) asking questions (e.g., *Where da' green one go? Why can't it fits? Where's the U?)*; and (12) affect expression (e.g., *I can't find it!; I don't know where this goes; I'm mad at this one [points] 'cause I can't put it on!*). Consistent with previous work (Berk, 1986; Winsler et al., 2005), private utterances classified into categories 8 through 13 were conceptualized as 'mature private' speech.

Social utterances were classified into one of seven mutually-exclusive categories (see Table 2b): (1) attention-seeking (e.g., *Mom?, Look, mom!*); (2) sharing/telling (i.e., trying to tell someone about the puzzle or share the experience with them; e.g., *Mom it fits here!, Look, mom, I found a diamond!, I did it, mom!*); (3) help-seeking (e.g., *Will you help me?, Right here? [looks, points], Where does this one go?*); (4) task-resistance (e.g., *I can't do this by myself, This puzzle is too hard!, Mommy it won't match!*); (5) off-task/irrelevant (e.g., *Are we upstairs? Mommy, why are you reading a magazine?*); (6) conversational replies/non-independent (i.e., direct replies to another person's comments or questions that were unrelated to the puzzle; e.g., Mother: *We've been here before* / Child: *Yeah, I know*); and (7) unintelligible.

Training reliability coding. Once a coding scheme was established, the author and a trained coder watched and coded 10 videos together for training purposes. Subsequently, 20% (N = 31) of the videos were coded independently for reliability. All coding was accomplished by watching the DVD recording of the task session with a copy of the transcript. Codes were originally entered into an Excel spreadsheet that contained formulas for summing the total number of utterance codes present in the entry columns. Summing across all 31 transcripts, there was a total of 523 utterances (M = 16.87). Of these 523, complete agreement was achieved for 88 percent. Of the 63 disagreements, most (60%) were about the specific code to apply for a social or self-directed utterance; only 25 times (5% of all utterances coded for training reliability) was there disagreement as to whether an utterance was social or self-directed. All videos were subsequently coded with a 15% reliability overlap.

Inter-rater reliability. Inter-rater reliability was evaluated for the 'mature private' and social 'help-seeking' speech composites. Because the values generated from coding and that were entered into the dataset for analysis were continuous, Intra-Class Correlations (ICCs) were computed to establish inter-rater reliability (Hallgren, 2012). The ICCs yielded from the coding training reliability analysis and subsequent 15% reliability overlap were acceptable (see Table 3).

CHAPTER IV

RESULTS

Analytic Plan

To address the first study aim, a growth curve was fit to the repeated measures EEG power data. With this technique, questions regarding the average pattern of growth in the frontal cortex as well as how individual differences in growth are associated with IC, can be addressed. An advantage of the structural equation modeling (SEM) approach to growth curve modeling (vs. multilevel modeling) is that growth is estimated as latent factors (intercept, slope), which allows for shared error attributable to the measure to be removed from parameter estimates (Muthén & Curran, 1997). The slope factor indicates the average amount of change during the study period whereas the intercept represents the average level of performance of the variable undergoing change; it is often centered at the first time point and interpreted as the 'initial level' (Grimm, Ramm, & Estabrook, 2017). Additionally, as a latent (i.e., unobservable) construct, children's IC could be measured as a latent factor from their performance across battery of experimental tasks and adults' reports of their abilities and behavior problems. Thus, to address the first aim, a growth curve was fit to the resting frontal EEG power data at 10, 24, and 36 months, and the intercept and slope terms were examined as predictors of IC at 4 years.

To address the second aim, observed (i.e., manifest) variables representing the overall amount of speech children produced during the puzzle task (utterances per minute), the proportion of their private speech that was mature (i.e., semantically on-task, coordinated with task-relevant actions), and the proportion of their social speech that was ‘help-seeking’ were calculated and examined as predictors of IC in a separate path analysis. Subsequently, to address the final aim, speech variables were entered into the larger structural model and their direct associations with latent growth factors and IC were examined. Indirect effects from growth factors to IC (through speech variables) were examined using bias-corrected bootstrapping, which has been shown to generate the most accurate confidence intervals for indirect effects, reducing Type I error rates and increasing power over other similar tests (MacKinnon, Lockwood, & Williams, 2004).

Preliminary Analyses

Preliminary analyses were conducted in SPSS (v. 25) and involved the creation of composite variables, assessing the normality of distributions, and selection of model covariates. First, frontal EEG power composites were calculated by averaging the power values from medial frontal (F3/4), lateral frontal (F7/8), and central (C3/4) scalp sites at each timepoint (see Figure 2). These sites were chosen because they collectively lie above the frontal cortex and have been implicated in the theoretical and empirical literature as being important for WM, IC, and expressive communication (Bell & Fox, 1994; Marshall et al., 2013). In the current study sample, power values at these sites were highly correlated within timepoint and mean values demonstrated the expected pattern of increasing with age (see Table 4). These three composites served as indicators of the latent growth factors in the measurement model.

An IC composite was calculated from the observed and questionnaire measures; descriptive properties and bivariate correlations among these variables are displayed in Table 5. Although IC is best conceptualized as a latent construct, because the study sample consisted of fewer than 200 participants, IC was measured as a manifest composite to reduce the number of estimated parameters in the model and to protect against Type II error. Based on the pattern of intercorrelations, the Day-Night task proportional score and CBQ IC scale score were excluded from the composite, as they were not significantly correlated with other variables. The other five variables (3 observational tasks, 2 questionnaire measures) were converted to standardized z-scores and averaged to yield a single composite (the BRIEF 'Inhibit' scale score was reverse scored prior to standardizing).

Utterances per minute was calculated by summing the number of private and social utterances and then dividing by the task length in minutes. Subsequently, two proportional scores were created by (1) dividing the number of mature private utterances by the total number of private utterances and (2) dividing the number of social 'help-seeking' utterances by the total number of social utterances. These three variables were used in the analyses. As depicted in Table 6a, the amounts of speech from categories included in the 'mature private' composite were modestly intercorrelated with one another (justifying the creation of the composite). As depicted in Table 6b, the amount of 'help-seeking' speech was significantly positively corelated with the amounts of 'attention-seeking' and 'sharing/telling' speech. However, because those kinds of utterances would not theoretically be turned towards the self as mature private speech, they were not summed to yield a composite. Ten children produced no speech during the task and were thus missing data for both speech proportional scores; 17 children produced no private speech and 7 produced no social speech and were similarly missing data for the private and social speech proportional scores.

Descriptive properties and bivariate correlations among study variables are displayed in Table 7. As depicted there, frontal EEG power composites were significantly positively correlated with one another but were not significantly correlated with IC or the speech variables. The 'mature' private and 'help-seeking' social speech composites (reflecting the *amounts* of this speech) were not significantly correlated with one another, indicating that greater amounts of 'mature' private speech were not necessarily accompanied by greater amounts of 'help-seeking' social speech; neither composite was significantly correlated with IC. However, the 'mature' private and 'help-seeking' social speech proportional scores (reflecting the proportion of private utterances that were 'mature', and the proportion of social utterances that were 'help-seeking') were significantly positively correlated with one another (R = .22, p = .02); both scores were significantly positively correlated with IC (Private: R = .22, p = .02; Social: R = .28, p = .00). Thus, when children's private speech was proportionally more mature, and when their social speech was more exclusively devoted to help-seeking, their IC tended to be greater at age 4.

Finally, model covariates were selected based on theory, previous research, and the results of statistical tests. First, based on previous research, sex group differences in all study variables were examined. With respect to EEG measures, girls had marginally lower resting frontal power values at 10 months (M = 2.46, SD = .50) than boys (M = 2.60, SD = .48), $t(164) = 1.90$, $p = .06$, 95% CI [-.01, .30]. Additionally, girls had significantly greater IC (M = .14, SD = .70) than boys (M = -.19, SD = .75), $t(160) = -2.83$, $p = .01$, 95% CI [-.55, -.10]. There were no significant sex differences in speech variables, although girls tended to have social speech that was proportionally more 'help-seeking' (M = .48, SD = .32) than boys (M=.38, SD = .33), $t(136) = -1.78$, $p = .08$, 95% CI [-.21, .01]. Given these differences, sex was included as a covariate in all models. Second, because the experimenter did not leave the room during the puzzle task for some (21%) children, which could influence the amount of speech children produced, a dummy variable ('experimenter status') was included as a covariate in the models containing speech variables (1 = experimenter remained in the room); this variable was significantly negatively correlated with utterances per minute (R = -.16, $p = .04$). Last, an observed measure of 'puzzle task engagement' was significantly positively correlated with IC (R = .33, $p = .00$) and the 'help-seeking' social speech proportional score (R = .37, $p = .00$); a marginally positive association between this variable and the private speech maturity score was also observed (R = .17, $p = .07$). Thus, to ensure that the hypothesized associations between speech and IC were not due to differences in behavioral engagement (i.e., children who produced off-task speech could have been up and about during the task in addition to having less mature speech), this variable was also included as a covariate in the models.

Analyses Addressing Research Questions

Analyses addressing research questions were conducted in Mplus (v.8; Múthen & Múthen, 2012), and full information maximum likelihood (FIML) was used to handle missing data. For clarity, unstandardized path estimates are depicted in-text and standardized estimates are depicted in figures.

1) Is there a significant amount of change in children's resting frontal EEG alpha power values from 10 months to 3 years? This question was addressed by fitting a growth curve to the resting frontal EEG power data at 10, 24, and 36 months. Based on theory and previous research, a linear growth model (which contains slope and intercept factors) was expected to fit better than a 'no-growth' model (which contains only an intercept factor), and the mean of the linear slope was expected to be positive and significantly different from zero.

First, the 'no-growth' model was conducted, in which the frontal EEG power composites from 10, 24, and 36 months were modeled as indicators of a single latent growth factor (intercept); all factor loadings were fixed to one. This model did not fit well: $\chi^2(6) = 126.46$, $p = .00$; RMSEA = .33 [.29 - .39]; CFI = .00. Subsequently, a linear growth model was conducted by adding a latent slope factor to the model. Factor loadings for the 10-, 24-, and 36-month EEG composites were set to 0, 1.4, and 2.6, respectively; these values represent the time difference from the reference timepoint (10m) in proportion to the reference timepoint (e.g., 24 months – 10 months equals 14; 14 divided by 10 equals 1.4). This model fit well: $\chi^2(2) = 1.78$, $p = .41$; RMSEA = .00 [.00 - .14]; CFI = 1.0. Because the difference in chi square for these models exceeded the critical value of 13.28 (χ^2_Δ = 124.68), it was concluded that the linear growth model explained the data significantly better than the no-growth model.

Subsequently, because the residual variance for 3-year EEG was slightly negative (-.07) in the linear growth model, it was constrained to be zero and the model was rerun; this approach is recommended when the negative values are small and nonsignificant (Muthén, 2005). This model fit well: $\chi^2(3) = 5.99$, $p = .11$; RMSEA = .07 [.00 - .16]; CFI = .96. As in the previous model, female sex was not correlated with the intercept but was significantly positively correlated with the slope (R = .02, $p = .04$). Subsequently, the means of the latent growth factors (i.e., fixed effects) were examined, and both parameter estimates were significantly different from zero (Intercept = 2.52, $p = .00$; Slope = .18, $p = .00$). Thus, on average, children's initial level of resting frontal EEG power was 2.52 and increased by approximately .18 per unit of time. Thus, there was support for the first hypothesis, that children's frontal cortical maturity, as indexed by resting frontal EEG power values, would increase significantly from 10 months to 3 years.

2) Is variation between children in the initial levels and amount of change in resting frontal alpha power from 10 months to 3 years significantly associated with variation in their IC at 4 years? The variance estimates for both latent factors were significant (Intercept = .09, $p = .04$; Slope = .02, $p = .01$), indicating there was enough variability in these parameters for them to serve as predictors in the larger structural model. Based on theory and previous research, the intercept and slope parameters were both expected to be significantly positively associated with IC.

This model fit well: $\chi^2(4) = 6.35$, *p* = .18; RMSEA = .06 [.00 - .14]; CFI = .97. As in the previous model, female sex was significantly positively associated with the slope (B = .07, *p* = .04), indicating that girls exhibited greater increases in resting frontal EEG power values from 10 months to 3 years than boys. Additionally, female sex was significantly positively associated with IC (B = .35, *p* = .01). However, the direct effect estimates from growth factors to IC were not significant. Thus, there was not support for the hypothesis that variation between children in the initial levels or amount of change in their frontal cortical maturity from 10 months to 3 years would be positively associated with their IC at 4 years.

3) Is the amount and maturity of children's private speech during problem-solving at 3 years significantly associated with their IC at 4 years? 4) Is children's social speech during problem-solving also significantly associated with their IC at 4 years? To address these research questions, IC was regressed onto the three speech variables (utterances per minute, private speech maturity, social speech maturity) in a separate path analysis; child sex, experimenter status, and puzzle task engagement served as covariates. Based on theory and previous research, a significant negative association between the overall amount of speech (utterances per minute) and IC was expected, a significant positive association between the maturity of children's private speech and IC was expected, and a significant positive association between the proportion of children's social speech that was 'help-seeking' and IC was expected.

This model fit well: $\chi^2(3) = 2.02$, *p* = .57; RMSEA = .00 [.00 - .11]; CFI = 1.0 (see Figure 3). First, associations between covariates and speech variables were examined. As in the previous model, female sex was significantly positively associated with IC (B = .26, p = .01) but was not significantly associated with any of the speech variables. Observed task engagement was significantly positively associated with both speech proportional scores (Private: B = .10, p = .02; Social: B = .17, p = .00), indicating that when children were observed as being more engaged with the puzzle their private speech tended to be more mature and their social speech tended to contain a greater proportion of utterances classified as help-seeking. Additionally, observed task engagement was significantly positively associated with IC (B = .23, p = .01). Experimenter status was significantly negatively associated with utterances per minute (B = -2.42, p = .03), indicating that children tended to produce less speech when the experimenter was in the room; this variable was not significantly associated with the speech proportional scores. Utterances per minute was not significantly correlated with the speech proportional scores; however, the speech proportional scores were marginally positively correlated with one another (R = .02, p = .09). Thus, the overall amount of speech children produced in the task was not related to the maturity of their private speech or the proportion of their social speech that was 'help-seeking', but when children's private speech was more mature their social speech tended to contain a greater proportion of utterances classified as 'help-seeking.'

Subsequently, the associations between speech variables and IC were examined. Utterances per minute was significantly negatively associated with IC (B = -.02, p = .04), indicating that when children produced a greater amount of speech their IC at age 4 tended to be lower. Both speech proportional scores were significantly positively associated with IC (Private: B = .49, p = .02; Social: B = .39, p = .046), indicating that when children's private speech was more mature and when their social speech was proportionally more 'help-seeking,' they tended to have greater IC at age 4. Thus, there was support for all three hypotheses concerning the relations between speech during problem-solving at 3 years and IC at 4 years. Twenty-three percent of the variance in IC at 4 years was explained in this model.

5) Is variation between children in the initial/overall levels of resting frontal alpha power from 10 months to 3 years significantly associated with variation in the amount of speech they produce during problem-solving at 3 years? 6) Is variation between children in the initial/overall levels of resting frontal alpha power from 10 months to 3 years significantly indirectly associated with their IC at 4 years through an influence on the amount of speech they produce during problem-solving at 3 years? To address these research questions, the three speech variables were entered into the larger structural model as mediators and the significance of direct effect estimates with other variables were examined. Subsequently, indirect effects from the intercept and slope parameters to IC (through utterances per minute) were estimated using bias-corrected bootstrapping (10,000 draws), and confidence intervals generated from this procedure were examined.

This model fit well: $\chi^2(16) = 18.97$, p = .27; RMSEA = .03 [.00 - .08]; CFI = .98. Female sex was still significantly positively associated with the slope factor (B = .07, p = .04) and IC (B = .29, p = .02). All significant associations between speech variables and IC remained significant in this model; although, the significant negative association from utterances per minute to IC became marginal (p = .06). However, the latent growth factors were not significantly associated with the speech variables or IC; none of the indirect effects were significant, as both confidence interval ranges contained zero. Thus, there was not support for the hypothesis that variation between children in the overall level of frontal cortical maturity from 10 months to 3 years would be associated with the amount of speech they produced during problem-solving at 3 years, or the hypothesis that the amount of speech during problem-solving at 3 years would mediate a relation between the overall level of frontal cortical maturity from 10 months to 3 years and IC at 4 years.

CHAPTER V

DISCUSSION

The ability to inhibit inappropriate behaviors in accordance with rules and societal standards is one of the most important skills for young children to develop. IC in the preschool period is particularly important because it may support the adjustment to formal schooling and establish a foundation for academic and social competence across childhood. Children's biologically-based capacity for WM and their use of language in challenging contexts may both contribute to individual differences in their IC. Thus, the purpose of this study was to examine developmental change in children's frontal cortical maturity and their speech during problem-solving as predictors of their IC in preschool.

Frontal Cortex Maturation and Inhibitory Control

The frontal cortex is the last cortical region to mature in humans, and rapid improvements in IC are observed across the fourth year, when synaptic density in the frontal cortex may be greatest. Because IC may crucially depend on neural resources in the frontal cortex associated with WM, variation in the amount or rate of maturational growth in the frontal cortex across the first few years of life could be related to variation in preschoolers' IC skills. However, due to the invasiveness of many neuroimaging techniques, there has been very little investigation into the individual differences that may exist in this important developmental process (e.g., amount of growth).

Measures of resting EEG activity in the alpha frequency range increase at frontal scalp sites in early development (Marshall et al., 2002) and may provide an index of frontal cortical maturity associated with WM/IC capacity. Although positive associations between resting frontal alpha power and IC have been reported in preschoolers (Wolfe & Bell, 2004), it is unclear whether they reflect stable individual differences that were present in infancy or maturational changes that occurred across the toddler years. No study has examined how the amount of change in frontal cortical maturity during this time is associated with IC in preschool. Thus, the first aim of the study was to estimate developmental change in children's frontal cortical maturity from 10 months to 3 years in a growth curve from repeated measure of resting frontal EEG power, and to examine how variation between children in the initial levels and amount of change were associated with variation in their IC at 4 years.

As expected, a linear change model fit the data better than an intercept-only model, suggesting that variation in the repeated measures EEG power data was not fully explained by individual differences that remained stable over time; rather, the variation was better explained by the inclusion of a latent factor associated with linear change. This finding is consistent with the idea that the toddler years are a period of maturational growth in the frontal cortex. Additionally, there was a significant amount of variability between children in both growth factors, which were not significantly correlated with one another. Thus, although a pattern of positive linear change was characteristic of the sample at large, individual children may have started out with very different levels of frontal cortical maturity and/or exhibited very different amounts of change across the study period. For example, the lowest intercept and slope combination was 2.06 and .11 whereas the greatest combination was 3.02 and .43; thus, some children not only exhibited lower initial levels, but also showed less growth (and vice-versa). Had the intercept and slope been significantly negatively correlated, it would have suggested that children with lower initial levels of frontal cortical maturity tended to catch up with their peers by 3 years. Thus, although there was linear change in children's resting frontal EEG alpha power from 10 months to 3 years consistent with frontal cortical maturation, there was considerable variability in the measure that remained stable over time. Modeling developmental EEG changes in a growth curve is therefore useful because it enables researchers to examine how variation between children in the stable and changing aspect of the measure are uniquely associated with other variables.

Although there was a significant amount of variability between children in the intercept and slope factors, this variation was not significantly associated with their IC. Thus, there was not support for the hypothesis that variation between children in the initial levels or amount of change in frontal cortical maturity across the toddler years would account for significant variance in their IC in preschool. Importantly, however, these results do not indicate that maturation of the frontal cortex is not important for the development of IC or that variation between children in the amount of maturational change does not contribute to individual differences. Possibly, the study was underpowered due to sample size. Monte Carlo stimulation studies have suggested, for instance, that to achieve enough statistical power to detect effects in relatively simple growth curve models (e.g., 1 intercept, 1 slope, 1 covariate), more than 200 participants may be necessary (Muthén & Muthén, 2002). Measurement choices could also have contributed to the null effects. For instance, the IC composite may have been too broad in scope to capture significant associations with physiology. Aside from the maternal report measure (BRIEF), all the other IC measures included in the composite pertained to children's behavior on the day of their 4-year lab visit. In contrast, the BRIEF covers a wider range of scenarios and over a much longer period of time (2 weeks). Thus, although the BRIEF was significantly correlated with the other measures, it could have introduced noise into the IC composite that obscured its associations with the slope. However, theoretical explanations for the null findings are also possible.

Possibly, the hypothesized positive association between the slope and IC would be moderated by aspects of children's language experiences across the toddler years. The reason that the linear slope was expected to be positively associated with children's IC at 4 years is because preschoolers' IC is thought to be verbally-mediated, and the 10- to 36-month period is when children first begin to use language; frontal cortical maturation during this time could be uniquely associated with children's IC at 4 years. However, children's brain development does not happen in a vacuum, and their language experiences (e.g., exposure to/production of words) could be an essential part of the process by which the frontal cortex becomes specialized for holding verbal information about context (e.g., rules) online. Thus, the amount of change in children's frontal cortical maturity across the toddler years may not be positively associated with children's IC at 4 years if their exposure to words or production of words during this time is relatively low. Participants in the study came from a diversity of backgrounds;

in examining whether the amount of change in children's frontal cortical maturity across the toddler years is associated with their IC in preschool, future studies should examine whether aspects of their language experience (e.g., vocabulary, exposure to daycare) operate as moderators.

It is also possible that if measures of 4-year EEG had been included in the growth curve model significant positive associations between the slope and IC would have been observed. The fourth year of life is when rapid improvements in IC are observed; increases in frontal cortical maturity during this time could be especially important for IC at 4 years. However, previous work suggested that the frontal cortex enters a synaptic pruning phase sometime around 3 or 4 years (Huttenlocher & Dabholkar, 1997), which could involve a decrease in frontal EEG alpha power values. Because pruning of unnecessary neural connections is thought to promote the efficiency of existing neural pathways, it is unclear how growth in children's resting frontal cortex activity during particular time would be associated with their IC at 4 years. Thus, a goal of this study was to investigate the significance of brain growth up to age 3 for children's IC at age 4. However, future studies investigating developmental change in children's frontal cortical maturity in a growth curve from repeated measures of EEG should incorporate more than three timepoints to explore patterns of nonlinear growth.

Although it was not a focal research question it is important to discuss the finding the female sex was positively associated with the slope factor and with IC. That girls tend to have greater IC than boys in the preschool period has been reported across multiple studies (e.g., Carlson & Moses, 2001; Kochanska, Murray, & Coy, 1997). However, few theoretical explanations for these associations have been proposed. In this study, female sex was also significantly positively associated with the latent slope factor, suggesting that girls exhibited greater increases in frontal cortical maturity across the toddler years than boys in addition to exhibiting greater IC at 4 years. Although the slope was not significantly associated with IC in this study, theoretically, sex differences in the amount or rate of maturational growth in the frontal cortex across the toddler years could help explain the observed sex differences in IC and various other competencies that emerge in early childhood. Future work should actively investigate the potential influence of sex differences in frontal cortical maturation on self-regulatory development.

Speech during Problem-Solving and Inhibitory Control

Although IC may continue to depend on neural resources in the frontal cortex associated with WM, by early childhood, children’s ability to inhibit contextually-inappropriate behavior may additionally involve using language internally, and their speech during problem-solving may play an important role in this emerging ability (Luria, 1961; Diamond et al., 2002). Previous work suggested that preschoolers with lower IC talk more than other children in problem-solving contexts (Winsler et al., 2000). However, positive associations between the maturity of children’s private speech and their IC in preschool have been reported (Winsler et al., 2003). What remains unclear is whether those associations are unique to private speech or whether they could be partially explained by characteristics of children’s social speech. Very little work has investigated the associations between private speech during problem-solving and IC longitudinally in the preschool period, and few studies have also focused on children’s social speech.

Thus, a second aim of the study was to examine children's speech during problem-solving at 3 years, and to assess how variation between children in the amount and maturity of their private and social speech was associated with their IC at 4 years.

As hypothesized, the overall amount of speech children produced during problem-solving at 3 years was significantly negatively associated with their IC at age 4. Specifically, as the number of utterances children produced during a difficult puzzle task increased, their IC one year later tended to be lower. An utterance is understood as the smallest unit of speech that can stand alone and convey a discrete meaning; a greater number of utterances therefore indicates a greater amount of discrete and meaningful speech acts. That 3-year-olds who produced more utterances per minute during problem-solving in this study tended to have more difficulty inhibiting inappropriate behavior at 4 years is consistent with earlier studies (Winsler et al., 2000). This association is unlikely to be causal, however, in the sense that producing speech during problem-solving led to a deterioration in children's ability to think in words or plan actions in novel or challenging contexts. Rather, the amount of speech children produce in problem-solving contexts may be reflective of an underlying trait or characteristic to act on impulse or express themselves when challenged. Vygotsky thought that frustration was the 'secret ingredient' to eliciting private speech in children. Because children's speech in this study was observed from a challenging puzzle task designed to elicit frustration, those who produced a greater number of utterances may have been more frustrated by the task, which could indicate a greater need for IC skills. Because an underlying disposition to react to frustrations and challenges may both cause a child to produce more speech during problem-solving and place them at relatively greater risk for having problems with IC, future studies should incorporate measures of observed emotion or temperament (e.g., negative affectivity, motor activity) to examine how the amount of speech produced during problem-solving is related to other traits and tendencies of children.

Importantly, although the negative association between utterances per minute and IC was significant in the structural model, the bivariate correlations between these variables was not significant. Only when variables reflecting the content of children's speech were controlled for in the path model was the overall amount of speech significantly negatively associated with IC. Because utterances per minute was not significantly correlated with the speech proportional scores, this could indicate that the combination of these variables is important to consider in relation to IC. However, because the influence of 'experimenter status' on utterances per minute was not controlled for in the bivariate correlations, the lack of a significant correlation between utterances per minute and IC could be partially due to measurement error; the correlation coefficient was not far off from being significant (p = .15). Another possibility is that the effect was mostly explained by children's private speech (or vice-versa). Because the overall amount of speech regardless of orientation was hypothesized to be negatively associated with IC, to conserve parameter estimates, private and social utterances were summed to yield a single measure of speech amount. In hindsight, however, it may have been important to examine whether the amounts of private and social speech during problem-solving were related to children's IC in similar ways. Thus, although the results are consistent with the hypothesis, additional work is needed to understand the unique contributions of private and social speech in the relation between speech amount during problem-solving and IC.

As expected, the proportion of children's private speech that was classified as 'mature' was positively associated with their IC. Mature private speech was conceptualized as self-directed speech that was semantically related to the child's goals or feelings about the task, or that was coordinated with the child's ongoing task-related manual activity (Berk, 1986). Thus, this finding indicates that when children's private speech was more meaningfully related to what they were doing or trying to do, their IC at age 4 tended to be greater. Theoretically, children whose private speech at 3 years was proportionally more mature may have been better able to use language internally to voluntary control their behavior at 4 years. This finding is also consistent with Winsler et al. (2003), who reported significant associations between the maturity of children's private speech and their teacher-reported social skills and externalizing problems, measures that may partially reflect children's IC. However, it is unclear from the results whether the presence of mature private speech or the absence of immature private speech is responsible for the effect.

Overall, mature forms of private speech were more common than immature forms; about 70% of all private utterances transcribed from the puzzle task were classified as mature. Additionally, 45% of children did not produce any immature private speech whereas most (79%) children produced at least one mature private speech utterance. Thus, the presence of immature private speech may be driving the positive association between private speech maturity and IC. Importantly, though, this association was not explained by task engagement (which was controlled); both mature and immature forms of private speech almost always accompanied task-relevant activity. However, mature private speech had a meaningful connection to that activity whereas immature private speech was semantically off-task, repetitive, exclamatory, or self-stimulating. When children produced immature private speech, it seemed as though they were not even thinking about what they were saying. Thus, given the significant positive association between private speech maturity and IC, the presence of immature private speech during problem-solving may serve to promote impulsive action in challenging contexts over time.

Another possibility is that the presence of immature private speech is a marker for low receptive verbal ability, which was not measured in this study. That is, when children's private speech contained more immature content (e.g., humming, repeating sounds/syllables), their mature private speech may have also been less complex in terms of vocabulary or number of words per utterance. Additionally, there were multiple categories of speech that comprised the mature private composite; some were considered mature because of their semantic relation to the child's goals and feelings about the task (e.g., asking questions, planning, verbalizing affect) whereas others were considered mature because of their temporal relation to the child's ongoing activity (e.g., saying 'This goes *here'* while putting a piece on). To be consistent with previous research they were combined into a single composite, but possibly, these kinds of mature private speech are related to IC in different ways. Children who produced any immature private speech may have been less likely to produce mature private speech that was semantically-related to their ongoing activity (which was less common than speech-action coordination). Future studies should more closely examine how these different kinds of mature private speech are associated with children's IC.

Finally, as expected, 3-year-olds' social speech during problem-solving was also significantly associated with their IC at 4 years. Specifically, when children's social speech during the puzzle task contained a greater proportion of utterances that were classified as 'help-seeking' their IC at 4 years tended to be greater than when they produced other kinds of social speech. Theoretically, the speech children use to address their mothers in times of difficulty may be the same speech they ultimately use for themselves independently to resolve conflicts and solve problems. Compared to the other kinds of social speech observed in this study (e.g., off-task comments, sharing/telling about the puzzle, attention-seeking), 'help-seeking' may provide a foundation for mature private speech by promoting a constructive (vs avoidant, resistant) stance towards problem-solving. That is, when young children repeatedly address their caregivers for help when they are challenged (vs. complain or try to distract away from the problem), they may be more inclined to use private speech in ways that are self-guiding, planful, and purposive. This interpretation implies a causal, *indirect* association through the maturity of private speech. However, that the private and social speech proportional scores were uniquely associated with IC in the path analysis suggests that a direct association is possible. If the effects are independent, then children's private and social speech during problem-solving may influence their IC in similar ways. Future studies should examine children's speech during problem-solving longitudinally (e.g., 2, 3, and 4 years) and assess the stability and cross-lagged associations between the amounts and 'constructive focus' of their private and social speech.

It is also possible that the broadness of the IC measure in this study contributed to these 'independent' associations. Specifically, the private and social speech proportional scores could have been positively related to different IC measures that were included in the composite but that tap into different aspects of the construct. Experimental IC tasks are thought to tap into children's cognitive capacity for IC by requiring them to inhibit behavior according to arbitrary rules. Because children must learn the rules to play the tasks, their performance may be influenced by general aspects of executive function (e.g., WM, attention) in addition to IC. In contrast, adult report measures capture whether certain behavior problems suggestive of IC deficits (e.g., interrupting, continuing to laugh when others have stopped) have been recently present; these measures could be influenced by aspects of child temperament (e.g., surgency, positive anticipation) in addition to children's IC *ability*. Although the PSRA was significantly correlated with all other measures included in the IC composite, the BRIEF was only significantly correlated with one of the three experimental IC tasks. Thus, the private and social speech proportional scores could have been uniquely associated with the IC composite in this study if they were systematically explaining variance from these different measures.

Importantly, like the finding with private speech, the overall amount of social 'help-seeking' speech children produced during the task was not significantly associated with their IC whereas the proportion of their social speech that was classified as 'help-seeking' was significantly positively associated. Thus, children who *continuously* asked their mothers for help did not necessarily have greater IC at age 4; children who *exclusively* addressed their mothers to ask for help tended to have greater IC. Thus, producing other kinds of social speech in this task may be what is driving the effect. 'Off-task/irrelevant' social speech was often accompanied by off-task behavior (e.g., *I found an orange chair over here, mommy!)*. However, although the positive association between the social speech proportional score and IC was considerably weakened by the inclusion of 'task engagement' as a covariate, this control variable did not fully explain the association. Aside from 'off-task/irrelevant' social speech, the other social speech utterances tended to occur in the context of task engagement (e.g., sharing/telling about the puzzle, task-resistance). However, unlike 'help-seeking,' those kinds of speech were not necessarily constructive in the sense of completing the puzzle. For instance, one child repeatedly tried to show their mother interesting puzzle pieces, and it seemed as though they were more concerned with her than with the puzzle. Thus, it is possible that in addition to being more engaged in the task behaviorally, children whose social speech consisted mostly of 'help-seeking' may have been more motivated to achieve the goal of completing the puzzle than children who produced other kinds of social utterances (even if they were semantically on-task).

Interestingly, although the amount of 'task-resistant' social speech was positively correlated with the amount of 'off-task/irrelevant' social speech, this speech may be more constructive than it appears. One of the reasons why 'help-seeking' was conceptualized as 'mature social' speech in this study is because it could be turned towards the self as mature private speech. Quite often, children would ask their mother a question (*Where* *does this go?*) and then ask that same question to themselves, and it would be classified as mature private speech ('asking questions'). Like 'help-seeking,' but unlike the other social speech categories, 'task-resistant' social speech was often turned towards the self (as 'affect expression'). Possibly, 'task-resistant' social speech represents an indirect attempt to obtain help. That is, when children complained and whined about the task (e.g., *I don't know where this piece goes!*), they may have been trying to elicit help from their mothers, indirectly. Because of its relation to the mature private speech category 'affect expression,' future studies should more systematically examine how 'task-resistant' social speech is associated with children's IC.

Collectively, these findings indicate that the amount and content of children's speech during problem-solving at 3 years may contribute to variance in their IC at 4 years, and that social speech is equally as important to consider as private speech in this relation. However, additional work is needed to understand the underlying mechanisms and unique influences of private and social speech.

Frontal Cortex Maturation and Speech during Problem-Solving

The final aim of the study was to examine the overall level of frontal cortical maturity across the toddler years as a predictor of the amount of children's speech during problem-solving at 3 years. This exploratory aim was based on the idea that frontal cortical maturation, in addition to providing the neural resources for WM (which may directly support IC), involves an increase in the amount of inhibition being exerted over lower-level neural systems (e.g., limbic) that may promote expressive language in challenging contexts. However, despite a significant amount of variability between children in both the intercept and slope parameters, this variability was not significantly associated with variability in utterances per minute. Thus, there was not support for the hypothesis that the amount of speech during problem-solving at 3 years would mediate an association from the overall level of frontal cortical maturity across the toddler years to IC at 4 years. However, these null findings do not indicate that children's frontal cortical maturity is not related to their speech during problem-solving or expressive language development. Although utterances per minute may indicate the amount of discrete and meaningful speech acts that were produced in the task, this variable does not provide information about the number of words spoken, the uniqueness of those words, or the duration of time spent talking. Thus, although children who produced more utterances per minute arguably used speech more, they did not necessarily produce more speech in terms of the amount or complexity of words. Transcribing speech into units of meaning is important so that it can be coded based on functional meaning. However, to further probe the relation between frontal cortical maturity and the amount of speech during problem-solving, future studies should incorporate additional measures that capture aspects of speech complexity (e.g., mean length of utterance, total number of unique words).

It is also possible that the hypothesized negative association from the intercept to utterances per minute would only be significant among children who were prone to experiencing frustration. As mentioned, Vygotsky thought the experience of frustration was a catalyst for children's private speech. The reason why children with less mature frontal cortices were expected to produce more speech during problem-solving in this study is because they would presumably have less inhibition on their limbic systems, which may be activated in challenging contexts. However, if children are not temperamentally negative (due to a less reactive limbic system), then this relation may not hold. Thus, future studies should incorporate measures of temperament (e.g., negative emotionality) and observed emotion when examining the relations between children's frontal cortical maturity and their speech during problem-solving.

Strengths & Limitations

The current study is innovative in several respects and has several limitations that should be acknowledged. First, only a few studies have used EEG to examine developmental change in children's frontal cortical maturity in a growth curve, and no study has examined how variation in the overall level and amount of change are associated with individual differences in IC. The importance of frontal cortex function for young children's self-regulation abilities is widely accepted, as are the findings of early neuroimaging studies, which suggested the frontal cortex undergoes immense change in structure and function across the first few years of life. Yet, few attempts have been made to replicate those findings in samples of living children using non-invasive neuroimaging methodologies. Additionally, very little developmental EEG work has focused on individual differences or the relations between developmental EEG changes and behavior. The current study attempted to fill these gaps by modeling developmental change in children's frontal cortical maturity in a growth curve from repeated measures of resting-state EEG. Although individual differences in growth factors were not associated with children's IC, there are many promising avenues for future work.

Although the longitudinal analysis of EEG should be considered a strength of the study, there are limitations of EEG that should be acknowledged. A primary limitation of EEG is that it has poor spatial resolution: due to volume conduction, electrical activity generated from any particular group of cortical neurons becomes somewhat smeared as it passes through the scalp; as a consequence, electrical activity measured at any one particular site cannot be solely attributed to cortical activity directly beneath it (Davidson et al., 2000). Although site-specific associations between EEG and behavior are frequently reported, there may be better ways to measure children's frontal cortical maturity than by averaging the raw EEG power values from electrode sites overlaying the frontal cortex. Although studies have reported linear increases in resting frontal EEG alpha power values across infancy and early childhood, alpha activity is observed across the scalp (Stroganova et al., 1999), and alpha power values at posterior scalp sites could be increasing during this time as well. With development, however, as the frontal cortex continues to mature, the *proportion* of frontal to posterior alpha power should increase. Thus, a ratio measure (e.g., of frontal to posterior alpha power) could provide an index of frontal cortical maturity that is unrelated to variability in the raw power values; this should be explored in future studies.

Another measurement-related limitation of the study was its exclusive reliance on measures of EEG power, which only provide information about the excitability of cortical neurons. However, an important aspect of cortical function not measured in this study is connectivity. Some scholars have maintained that there are important changes across the fourth year in frontal cortical *organization* (i.e., how the frontal cortex communicates within itself and with other brain regions) that are important for children's emerging self-regulation skills. Specifically, Rothbart and her colleagues (2011) have proposed there is a shift in the brain's dominant attention network during this time. In their model, a 'fronto-parietal' network provides control over attention and behavior in infancy, but by 4 years, a 'cingulo-frontal' network (involving connections between the frontal and anterior cingulate cortex) is thought to become chiefly responsible for behavioral control. EEG coherence is a derived measure of EEG that reflects the temporal synchrony of activity at different scalp sites, and that may provide an index of connectivity between underlying cortical areas (Thatcher, 2012). Thus, an important direction for future work is to investigate how changes in the frontal cortex across the fourth year are associated with preschooler's IC skills; in investigating those changes, it may be useful to incorporate measures of both EEG power and coherence.

An especially innovative component of the study was its focus on children's speech, which is not typically measured or included in developmental research models. Although many studies have reported on the associations between receptive verbal ability and IC in the preschool period, children's actual use of language is rarely acknowledged or considered important in this relation. Although there is an extensive empirical literature on private speech in children, few studies have been longitudinal or focused on the preschool period. Given the rapid improvements in IC that have been observed across the fourth year, that children's speech during problem-solving in this study was observed at 3 years is a strength. Additionally, although mature private speech is thought to originate from children's verbal exchanges with adults, few studies on private speech have also examined children's social speech during problem-solving. Thus, the current study filled several gaps in the empirical and theoretical literature simultaneously by examining children's private and social speech during problem-solving at 3 years in relation to their IC at 4 years. That this speech was observed from sample of more than 150 children from diverse backgrounds is also noteworthy, as most studies on private speech have been conducted on very small samples.

That children's speech was observed from a naturalistic problem-solving task in which their mothers were in the room is a strength of the study. Most previous work has observed children's private speech from highly structured problem-solving tasks administered by an experimenter, which may limit the overall amount of speech as well as the kinds of social utterances that are produced. That the experimenter did not leave the room during the puzzle task for nearly a fifth of children, however, is a limitation, as it affected the amount of speech children produced. However, this is consistent with previous theoretical and empirical work on private speech which suggested that social context plays an important role in the amount of speech that is observed (Diaz, 1992). In a recent study, young children produced a significantly greater amount of private speech when they were in the presence of noncollaborative adult than when they were alone (McGonigle-Chalmers, Slater, & Smith, 2014), suggesting there may be a facilitative effect of social presence. However, that children in this study who completed the puzzle in the presence of two noncollaborative adults produced significantly fewer utterances per minute than children who completed the puzzle in the presence of just one suggests that *familiarity* of the other person is also a contributing factor.

Previous work has also suggested that children's perceived responsiveness of the person present also plays a role in how much speech they produce during problem-solving. Goudena (1987), for instance, reported that preschoolers produced a significantly greater amount of private speech during an independent puzzle task when they had just experienced the experimenter who was present as collaborative (vs. noncollaborative). Although, no significant differences in their social speech were observed. In this study, children participated in a 'collaborative puzzle' task with their mothers prior to participating in the independent puzzle task. Thus, the responsiveness of children's mothers during the previous interaction could have influenced characteristics of their problem-solving speech in this study. Possibly, children who have a history of sensitive, responsive caregiving would produce a greater amount (or proportion) of help-seeking speech than children whose caregivers have been less responsive to them in the past. Future studies should explore how the characteristic responsiveness of mothers is associated with the amount and content of children's speech during problem-solving.

Although the measurement context of children's problem-solving speech in this study is likely more representative of the real-world contexts in which children are solving problems than in previous work, at the same time, this design may have resulted in a loss of some experimental control. Although mothers were instructed not to interact with their children during the task, they were not as a group wholly compliant with this request. Consequentially, children may have had different opportunities for using speech in the task due to differences in maternal behavior, which is a limitation of the study. Most mothers said little or nothing to their child during the task. When comments were made, they were usually brief and undisruptive (e.g., *Mommy's gonna read her magazine now;* saying 'Okay' after child repeatedly tries to show them a puzzle piece). It was understandable when mothers addressed their children when they were off-task (e.g., *Don't touch that!; Come back here!).* However, a small group of mothers continuously responded to their child's comments or even initiated conversation. Whenever children's speech was in direct reply to something their mother said it was coded as 'conversational reply/non-independent,' but these utterances were not voided or excluded from the analyses. Thus, children with low proportions of social 'help-seeking' speech may have had several conversational replies contributing to that low proportion. Future studies should more systematically analyze this speech, given that in order for children to effectively produce private speech their mothers needed to not respond to them. Additionally, mothers who were unable to inhibit their dominant tendency to respond to their child's comments or questions in accordance with the experimenter's instructions may have poor IC themselves. Thus, incorporating caregivers' speech into the analysis of children's speech during problem-solving is important.

Another important direction for future research is to more systematically analyze children's social speech during problem-solving. Per the Winsler et al. (2005) coding manual, utterances were classified as social if they (1) contained a vocative or pronoun (e.g., *Mom, …*), (2) were accompanied by eye contact or gestures, or (3) if they occurred within two seconds of a previous social utterance. For many children, social utterances were almost always accompanied by eye contact. However, some children would address their mothers by name while looking down at the puzzle; possibly, these social utterances are more likely to be followed by private speech. That is, children may transition from talking to their mothers to themselves more readily if they are not looking at her while speaking. The proportion of children's social speech that is accompanied by eye contact could be an indicator of where they stand in the speech internalization process; this should be explored in future studies.

In conclusion, this study represents a methodologically innovative and theoretically grounded investigation of young children's self-regulation. The focus on IC in the preschool period is relevant, as children's IC at this particular time has been associated with greater social and academic competence in elementary school. The lack of significant findings involving growth curve parameters is disappointing, however, there are many different avenues for future research. The significant associations between speech variables and IC further underscore the need to examine developmental EEG changes across the fourth year, which could help explain the associations between speech and IC observed in this study. Additional research on children's speech as it might relate to their self-regulatory development is greatly needed. In that regard, a biopsychosocial approach that focuses on the biological underpinnings of expressive language and takes into consideration the social context of children's development is warranted.

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APPENDIX A

TABLES AND FIGURES

Table 1. Summary of Study Measures

Construct	Method	Task/Measure	10m	2y	3y	4y
Frontal Cortical Maturity	Electrophysiology	Baseline Frontal EEG Power (6-9 Hz)	X	X	X	
Problem-Solving Speech	Observation	Difficult Puzzle			X	
Inhibitory Control	Observation	Simon Says				X
		Day-Night				X
		Hand Game				X
		Three Pegs				X
	Parent-report	Children's Behavior Questionnaire				X
		Behavior Rating Inventory of Executive Functioning				X
	Experimenter-report	Preschool Self-Regulation Assessment				X

Table 2a. Frequency Counts and Descriptive Information for Private Speech Utterances.

Private Speech category		Frequency	Proportion	% N ≥ 1
1.	Unintelligible	87	7%	21%
2.	Nonword sounds	74	6%	21%
3.	Exclamations/transitions	52	4%	22%
4.	Repetition/wordplay	47	4%	17%
5.	Fantasy/imaginary dialogue	13	1%	3%
6.	Off-task/irrelevant comments/questions	34	3%	12%
7.	Describing materials	85	6%	21%
8.	Speech-action coordination	506	38%	55%
9.	Self-correction/feedback	89	7%	28%
10.	Self-description/planning	41	3%	18%
11.	Asking questions	158	12%	39%
12.	Affect expression	84	6%	24%
13.	Partially-internalized muttering	45	3%	18%

Note: There were 1315 self-directed utterances in total; the center column indicates the proportion of private utterances classified into the specified category; the right-most column indicates the proportion of children who produced at least one utterance of the specified category; categories 8 – 13 were conceptualized as 'mature'

Table 2b. Frequency Counts and Descriptive Information for Social Speech Utterances.

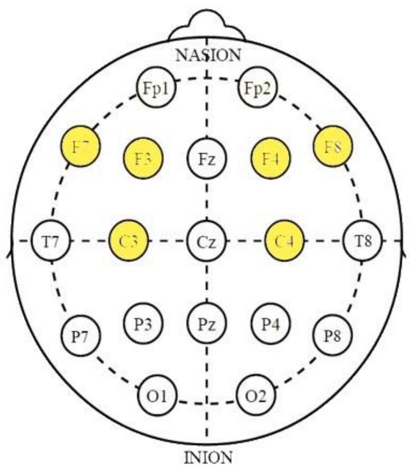
Social Speech category		Frequency	Proportion	% N ≥ 1
1.	Attention-seeking	172	13%	44%
2.	Sharing/telling	109	8%	30%
3.	Help-seeking	563	42%	70%
4.	Task-resistance	203	15%	44%
5.	Off-task/irrelevant	151	11%	32%
6.	Conversational reply	97	7%	26%
7.	Unintelligible	37	3%	12%

Note: There were 1,324 social utterances in total; the center column indicates the proportion of social utterances classified into the specified category; the right-most column indicates the proportion of children who produced at least one utterance of the specified category

Table 3. Inter-Rater Reliability Statistics for Speech Composites.

	Training Reliability ICC	Main Reliability ICC
N	31 (20%)	25 (15%)
Self (vs. social)	.99	.99
Mature Private Speech	.97	.99
‘Help-seeking’ Social Speech	.98	.99

Figure 2. Diagram of EEG Recording Sites



Note: Fp1/Fp2 not analyzed to avoid signal contamination from oculomotor artifacts.

Table 4. Descriptive Properties and Bivariate Correlations among EEG Variables.

			1	2	3	4	5	6
1.	F3_10			**.80	**.76	**.70	**.76	**.73
2.	F4_10				**.64	**.71	**.70	**.74
3.	F7_10					**.80	**.64	**.57
4.	F8_10						**.64	**.58
5.	C3_10							**.74
6.	C4_10							
		Mean	2.46	2.51	2.30	2.39	2.76	2.86
		SD	.54	.50	.49	.47	.74	.65
		Range	2.84	2.99	2.90	2.80	5.62	3.83
		Skewness	-.32	-.03	-.38	-.33	.48	.12

			7	8	9	10	11	12
7.	F3_24			*.81	**.74	**.70	**.79	**.72
8.	F4_24				**.77	**.82	**.73	**.79
9.	F7_24					**.81	**.67	**.63
10.	F8_24						**.62	**.67
11.	C3_24							**.82
12.	C4_24							
		Mean	2.69	2.72	2.53	2.62	3.00	3.04
		SD	.67	.58	.59	.52	.82	.75
		Range	4.50	3.05	3.88	3.22	3.90	4.33
		Skewness	-.46	-1.02	-0.43	-.70	-.13	-.69

			13	14	15	16	17	18
13.	F3_36			**.86	**.83	**.80	**.76	**.73
14.	F4_36				**.83	**.88	**.69	**.75
15.	F7_36					**.91	**.69	**.69
16.	F8_36						**.66	**.70
17.	C3_36							**.89
18.	C4_36							
		Mean	2.99	2.99	2.80	2.83	3.23	3.18
		SD	.43	.41	.41	.40	.59	.56
		Range	2.13	2.05	2.53	2.35	3.07	2.78
		Skewness	.05	-.07	.06	-.03	.66	.48

*Note: *p < .05; **p < .01*

Table 5. Descriptive Properties and Bivariate Correlations among Inhibitory Control Indicator Variables.

	1	2	3	4	5	6	7
1. CBQ - IC scale		**-.51	**.26	**.31	.04	.14	.16
2. BRIEF - Inhibit scale			**-.42	**-.34	-.04	.00	**-.25
3. PSRA - IC scale				**.39	.15	**.29	**.37
4. Simon-Says (% correct)					.02	.11	**.32
5. Day-Night (% correct)						.09	.05
6. Hand Game (% correct)							**.34
7. Three Pegs (% correct)							
Mean	4.70	25.31	2.11	.87	.71	.82	.51
SD	.82	6.00	.64	.29	.25	.20	.41
Range	4.50	28	2.91	1.00	1.00	.94	1.00
Skewness	-.34	.71	-.79	-2.21	-.80	-1.66	-.01
N	160	160	144	136	120	120	143

*Note: *p < .05; **p < .01*

Table 6a. Descriptive Properties and Bivariate Correlations among Private Speech Codes

		1	2	3	4	5	6	7	8	9	10	11	12	13
1.	Unintelligible		.00	*.17	-.05	-.05	-.04	**.35	.07	.06	.06	.06	-.02	-.06
2.	Nonword sounds			**.22	.11	.03	.01	-.06	**.22	**.33	.00	-.01	-.07	.05
3.	Exclamations/transitions				-.04	.05	.13	.14	**.21	**.23	.05	.10	.07	**.24
4.	Repetition/wordplay					**.23	*.17	.05	.08	**.31	**.22	*.20	-.09	-.01
5.	Fantasy/imaginary						.08	-.03	.05	.13	.05	-.02	.01	-.05
6.	Off-task							.03	.01	.15	.11	*.20	-.01	-.04
7.	Describing materials								.02	.00	.03	*.18	-.03	-.03
8.	Action coordination									**.32	*.17	*.20	.00	*.16
9.	Self-correction/feedback										**.33	**.24	.07	.01
10.	Describing self/planning											.04	.06	.03
11.	Asking questions												.12	-.03
12.	Affect expression													.05
13.	Partially-internalized													
	Mean	.26	.16	.07	.26	.19	.11	1.76	.13	.55	.28	.28	.30	.16
	SD	.78	.40	.52	.98	.45	.35	2.68	.37	1.01	.64	.90	.63	.41
	Range	4.35	2.00	4.41	8.64	3.00	2.48	13.02	3.28	7.62	4.00	8.23	3.69	2.42
	Skewness	3.20	2.89	7.31	6.80	3.51	3.88	1.95	4.93	3.33	2.92	5.80	2.66	3.34

*Note: *p < .05; **p < .01; units are in utterances per minute; categories 8 through 13 were conceptualized as mature private speech; categories 8 through 13 were included in the 'mature private' speech composite*

Table 6b. Descriptive Properties and Bivariate Correlations among Social Speech Codes

		1	2	3	4	5	6
1.	Attention-seeking		.05	**.27	.09	-.07	.13
2.	Sharing/telling			*.20	-.02	.00	.01
3.	Help-seeking				.00	-.14	-.07
4.	Task-resistance					**.28	-.04
5.	Off-task/irrelevant						.02
6.	Unintelligible						
	Mean	.60	.37	1.93	.73	.54	.13
	SD	1.16	0.82	2.24	1.20	1.24	.43
	Range	8.77	5.28	10.62	6.27	7.32	2.81
	Skewness	3.91	3.47	1.48	2.05	3.34	4.44

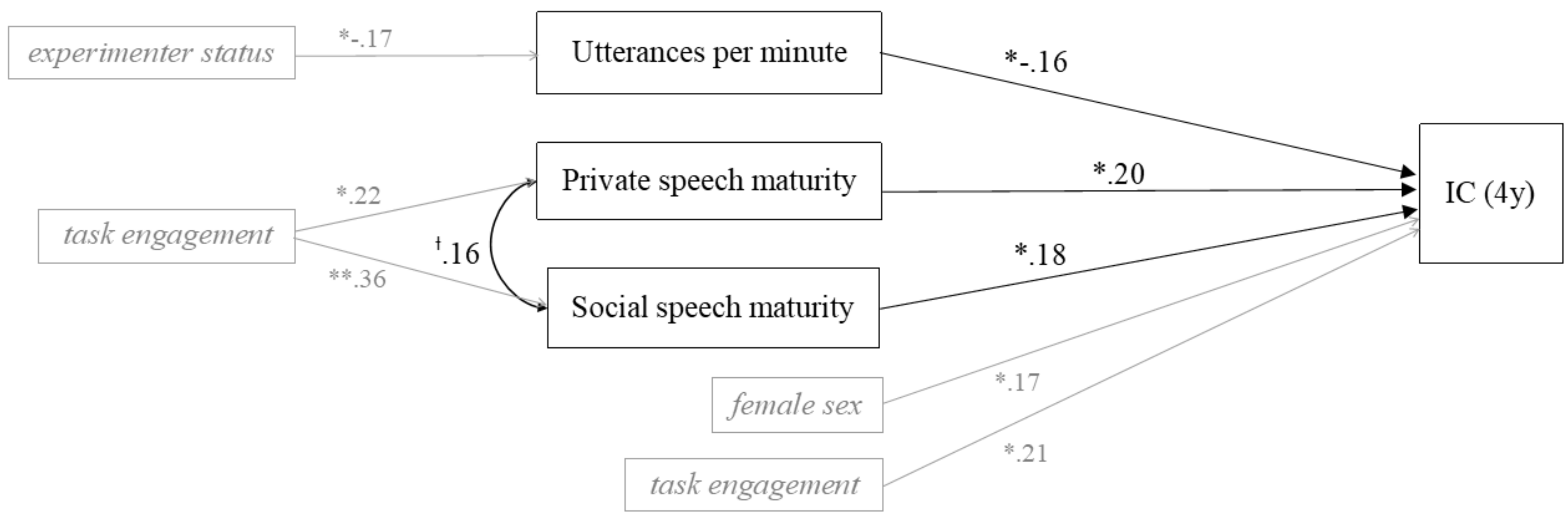
*Note: *p < .05; **p < .01; units are in utterances per minute*

Table 7. Descriptive Properties and Bivariate Correlations among Study Variables.

	1	2	3	4	5	6	7	8	9
1. Frontal alpha power (10m)		**.25	**.27	-.07	-.01	-.10	-.03	-.01	.01
2. Frontal alpha power (2y)			**.64	-.02	.02	-.09	.03	-.14	.04
3. Frontal alpha power (3y)				.02	.05	.02	.03	.00	.03
4. Utterances per minute					**.68	**.48	.13	.09	-.12
5. ‘Mature’ private speech (upm)						.11	**.40	*.22	-.02
6. ‘Help-seeking’ social speech (upm)							*.19	**.54	.04
7. ‘Mature’ private speech (%)								*.22	*.22
8. ‘Help-seeking’ social speech (%)									**.28
9. Inhibitory Control									
Mean	2.54	2.75	3.00	9.22	3.06	1.94	.69	.43	-.04
SD	.50	.59	.42	5.76	3.43	2.24	.31	.33	.74
Range	2.70	3.06	2.19	23.23	16.74	10.62	1.00	1.00	3.72
Skewness	-.19	-.53	.17	.32	1.26	1.47	-.85	.22	-.79
N	166	151	141	155	152	155	125	138	162

*Note: *p < .05; **p < .01; variables 5 and 6 represent the amount of speech (units are in utterances per minute); variables 7 and 8 are the proportional scores*

Figure 3. Diagram Depicting Associations between Amount and Maturity of Speech during Problem-Solving at 3 Years and Inhibitory Control at 4 Years



*Note: *p < .05; **p < .01; covariates depicted in light grey; only significant paths are depicted*