

Sources of variability in working memory in early childhood: A consideration of age, temperament, language, and brain electrical activity

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Abstract

This study investigated age-related differences in working memory and inhibitory control (WMIC) in 3½-, 4-, and 4½-year-olds and how these differences were associated with differences in regulatory aspects of temperament, language comprehension, and brain electrical activity. A series of cognitive control tasks was administered to measure WMIC ability, including the Stroop-like day–night and the yes–no tasks. Baseline and task electroencephalographic data were collected. The Children’s Behavior Questionnaire was used to assess caregiver perceptions of temperament with a particular interest in the effortful control and surgency factors, and language comprehension was measured with the Peabody–Picture Vocabulary Test-III. The results of this study demonstrated differential temperament–cognition relations for the three age groups, as positive associations were found between WMIC and effortful control for the 3½- and 4-year-olds and negative associations were found between WMIC and surgency for the 4½-year-olds. An increasingly robust relation between WMIC and language comprehension was demonstrated across the three age groups, as well as differential patterns of task-related brain electrical activity.

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Extraordinary advances in cognitive control occur during the early childhood years. Young children between the ages of 3 and 5 years show dramatic increases in regulatory processes described as inhibition of a response (Livesay & Morgan, 1991), compliance behaviors (Kochanska, Coy, & Murray, 2001), representational flexibility, perspective taking, and conservation (Flavell, Green, & Flavell, 1986; Piaget, 1952), comprehension of rules and execution of responses (Zelazo, Müller,

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Frye, & Marcovitch, 2003), global executive functioning (Welsh, Pennington, & Grossier, 1991), executive attention and attentional flexibility (Jones, Rothbart, & Posner, 2003), and working memory and inhibitory control (Diamond, Prevor, Callender, & Druin, 1997). The focus of the current project was the construct of working memory that highlights focused attention and inhibitory control (WMIC). The main goal of this study was to investigate differences in WMIC among children between the ages of 3 and 5 years of age and then to explain the age-related variability in terms of individual differences in temperament, linguistic ability, and patterns of brain electrical activity.

Working memory is well conceptualized by the organizational framework proposed by Engle (Engle, Kane, & Tuholski, 1999; Kane & Engle, 2002). Specifically, this perspective (1) incorporates the domain-specific components as described by Baddeley (i.e., the phonological loop and visuospatial sketchpad; Baddeley & Hitch, 1974), (2) includes a domain-free, limited capacity controlled attention component, (3) implicates the functioning of the dorsolateral prefrontal cortex (DL-PFC) and the anterior attention network, and (4) emphasizes individual differences in working memory. The attention component allows for the voluntary, focused, and exclusive processing and maintenance of task-relevant information in the presence of internal and/or external distracters. This component facilitates the inhibition of prepotent responses, error monitoring and correction, and decision making and planning and has been associated with the process of self-regulation (Engle et al., 1999; Posner & Rothbart, 2000). Thus, from this perspective, working memory may provide the foundation for the aforementioned cognitive control accomplishments. Although this framework of working memory was not formulated for young children, there is support for its applicability to this population. Research indicates that young children between the ages of 3½ and 7 years can perform tasks that require the self-regulatory skills of focused attention and inhibitory control. For example, in the Stroop-like day–night task (Gerstadt, Hong, & Diamond, 1994), as well as in Luria’s tapping task (Diamond & Taylor, 1996), children are required to pay attention to a set of rules, to remember and maintain the rules throughout the task, and to inhibit a dominant response (e.g., saying “day” when shown a drawing of the sun; tapping twice when the experimenter taps twice) in order to perform a non-dominant response (e.g., saying “day” when shown a drawing of a moon; tapping twice when the experimenter taps once). Results from studies using both tasks have demonstrated that young children could perform a task that requires the integration of working memory and inhibitory control, although not all age groups of children could perform this task equally well. Specifically, 3-year-olds provided no usable data and children between 3½ and 5 years of age had difficulty with the task; yet, older children (ages 6 and 7) performed well above chance levels (Diamond & Taylor, 1996; Gerstadt et al., 1994).

To what can we attribute these dramatic increases in WMIC during these early childhood years? Clearly, increases in cognitive control are associated with age, yet it is unlikely that these advances are simply a function of age alone. Indeed, regulatory processes, such as temperament characteristics and linguistic ability, have been associated with individual differences in cognitive control. Brain electrical activity from frontal scalp locations also has been associated with individual differences in WMIC performance (Wolfe & Bell, 2004; Wolfe & Bell, *in press*). The purpose of the current study, therefore, was to investigate age differences in WMIC ability in early childhood and how these age-related differences might be associated with temperament, linguistic ability, and patterns of brain electrical activity.

1. Associations with regulatory dimensions of temperament

Temperament has been defined as biologically based individual differences in emotional reactivity and the subsequent self-regulation of that reactivity (Rothbart & Bates, 1998). The

emergence of self-regulation begins late in the first year of life and culminates as effortful control in early childhood. Effortful control (EC) can be quantified as a higher order factor of temperament obtained from the Children's Behavior Questionnaire (CBQ; Rothbart, Ahadi, Hershey, & Fisher, 2001). Its subscales include low intensity pleasure (enjoyment related to situations involving low stimulus rate and complexity), inhibitory control (planning and suppressing inappropriate approach responses under instructions or in novel or uncertain situations), attentional focusing (maintaining attentional focus upon task-related channels), and perceptual sensitivity (detection of slight, low-intensity stimuli from the external environment). EC has been defined as the ability to suppress a dominant response in order to perform a subdominant one (Rothbart & Bates, 1998) and thus has clear implications for social (e.g., Eisenberg et al., 1996; Kochanska, Murray, & Harlan, 2000) and cognitive development (e.g., Carlson, Moses, & Breton, 2002; Rothbart, Ellis, Rueda, & Posner, 2003).

Conceptually, the temperament construct of EC is similar to the cognitive construct that is the focus of the current study, namely WMIC. Both constructs emphasize control and require the execution of certain processes (i.e., thoughts or actions) in the face of competing information or tendency. WMIC and EC are similarly defined as the ability to inhibit a dominant response to perform a non-dominant one and have similar neurological representations—both have been associated with the functioning of frontal brain systems, such as the DL-PFC and the anterior attention network (Posner & Rothbart, 2000; Rothbart & Bates, 1998; Ruff & Rothbart, 1996). The relation between WMIC and EC may be partly explained by their respective emphases on controlled attention. The WMIC construct emphasizes the maintenance of task-relevant information along with the engagement of focused attention allowing for manipulation of this information. Similarly, EC has been conceptualized as the control of attention combined with the control of behavior (Ruff & Rothbart, 1996). It is unlikely, however, that the relation between WMIC and EC is as simple as a shared focus on controlled attention. In fact, reciprocal and continuous transactions between these two constructs are probable, yet it is unclear which one provides the basis for the other. Perhaps WMIC capacity provides the basis for the effortful regulation of behavior as suggested with the previous control accomplishments of the early childhood years. As such, WMIC would allow for the assessment of the situation, allocation of attention resources, maintenance of goal-orientation, and execution of the appropriate response in the modality required to meet the specific demands of the task or situation (e.g. control of thinking or control of behavior). On the other hand, perhaps a certain temperamental disposition – one that is characterized by the effortful regulation of behavior – facilitates the development of cognitive control. Or is it that these two processes coactively or even independently develop? One focus of the current study was to investigate the nature of the relation between cognitive control (i.e., WMIC) and behavioral control (i.e., EC) in the early childhood years.

Previous research has supported an association between cognition and temperament in young children (Davis, Bruce, & Gunnar, 2002; Gerardi-Caulton, 2000; Wolfe & Bell, 2004). Cognitive control, including WMIC specifically, has been associated with EC and its respective subscales, as well as with surgency (SU)—a second factor related to behavioral control that is reliably obtained from CBQ scales. The SU factor includes the temperament scales associated with impulsivity (speed of response initiation), high intensity pleasure (enjoyment related to situations involving high stimulus rate and complexity), activity level (gross motor activity), positive anticipation (see above), and a negative contribution from shyness (Rothbart et al., 2001).

The temperament-cognition relation appears to be subtly influenced by the age of the child.¹ Specifically, performance of very young children (age 2½) on cognitive control tasks has been shown to be positively associated with temperament scales of focused attention, inhibitory control, low intensity pleasure, and perceptual sensitivity (i.e., all four scales that comprise the EC factor) and with caregiver ratings perceptual sensitivity – one scale from the EC factor – as well as attentional shifting at age 3 (Gerardi-Caulton, 2000). For these young children, cognitive performance was negatively associated with the anger/frustration scale, suggesting that children who perform better on the cognitive control tasks also have greater ability to regulate their anger and frustration. With slightly older children, performance on WMIC tasks at age 4½ revealed positive associations with two of the four scales that comprise EC – inhibitory control and attention focusing; a negative relation was found between WMIC performance and the anger/frustration scale, as well as with a subscale of the SU factor – the positive approach and anticipation scale (Wolfe & Bell, 2004). At age 6 years, cognitive control tasks have been shown to be positively related to parent-rated EC, but negatively related to parent-rated SU (Davis et al., 2002).

The current study investigated the developmental relations between cognitive control (WMIC) and the regulatory dimensions of temperament (EC and SU). We hypothesized that EC would be positively associated with WMIC performance, and that the strength of this relation would increase with age. We also hypothesized that SU would be negatively associated with WMIC performance. Further, we expected that EC would explain variance in WMIC ability above and beyond age.

2. Associations with language

Language has been noted as an essential component for executive problem solving and as the cornerstone of working memory (Goldman-Rakic, 1987; Shonkoff & Phillips, 2000). Baddeley's classic model of working memory (Baddeley & Hitch, 1974), as well as the more recent framework described by Engle (Engle et al., 1999), propose the existence of a linguistic component—specifically the phonological loop that allows for mental rehearsal of verbal and acoustic information.

Working memory and language have been the focus of much developmental research in attempt to understand the true nature of the association. Positive associations between the two constructs are consistently found (e.g., Adams & Gathercole, 1995; Davis & Pratt, 1995; Gathercole, Service, Hitch, Adams, & Martin, 1999; Wolfe & Bell, 2004). For example, Adams and Gathercole (1995) showed that working memory was associated with language ability, specifically verbal fluency,

¹ Age also appears to subtly influence the factor loadings of the CBQ. Rothbart et al. (2001) indicated subtle age-related differences in the subscales comprising the effortful control factor, particularly in loading strength. For the age 3 data and for the age 4 and 5 data, the subscales loading on the effortful control factor were low intensity pleasure (enjoyment related to situations involving low stimulus rate and complexity), inhibitory control (planning and suppressing inappropriate approach responses under instructions or in novel or uncertain situations), attentional focusing (maintaining attentional focus upon task-related channels), and perceptual sensitivity (detection of slight, low-intensity stimuli from the external environment), listed here in the order of decreasing association strength. However, when contrasting the 3-year-old with the 4- and 5-year-old data, the positive anticipation scale (excitement for expected pleasurable activities and which traditionally loads on the surgency factor) was notably related to the effortful control factor at age 3 and much less so for the older age groups. Further, Rothbart et al. (2001) noted that the perceptual sensitivity loading on the effortful control factor was attenuated in the 3-year-old sample. Although these age differences are subtle, they may provide insight into the changing organization of the regulatory aspects of temperament across the early childhood years and these changes may be associated with developing cognition across this same time period.

in 3- and 4-year-old children, as children with high working memory ability produced more complex spoken language than children with low working memory ability. In a second study by Gathercole and colleagues (Gathercole et al., 1999), receptive language was associated with working memory in 4-year-olds; this study further demonstrated that working memory capacity – that is, phonological short-term memory capacity – and not speech output skill, was associated with vocabulary knowledge. Thus, the phonological component of working memory appears important for learning new vocabulary, and in fact, the facilitation of language acquisition is one hypothesis regarding the functional significance of the phonological system (Baddeley, 2003). It also could be that having a good vocabulary facilitates the acquisition of new words (Gathercole & Baddeley, 1993). Using a cross-lagged panel correlational design, Gathercole and Baddeley (1989) showed the importance of the phonological loop in language learning as phonological ability at age 4 predicted vocabulary knowledge at age 5 but not vice-versa. Baddeley (2003) noted, however, that the relation between the phonological loop and vocabulary knowledge becomes more reciprocal as children get older and use their knowledge base to practice, learn, and incorporate new words.

Language has also been associated with the effortful regulation of behavior (Baddeley, 2003; Kopp, 1982). Luria's theory, in particular, places a strong emphasis on the role of language in higher mental processes (including the development thereof) but also on the control of behavior (Vocate, 1987). In general, the pattern of association moves from one of externalized control in which a child's behavior is regulated by vocalizations of an adult to behavior regulated by the child's own overt vocalizations, and finally to the child regulating his own behavior by internalized speech. Research investigating this association upholds the value of vocalization on the control of behavior, especially for young children. For example, Tinsley and Waters (1982) demonstrated the guiding force of vocalization as motor performance at age 2 was facilitated when verbal instructions were spoken aloud—regardless of whether the instructions were semantically relevant. Similar results were found for 4½ year old children, although the value of overt vocalization was more pronounced as task difficulty increased and the importance of semantic relevance increased with this age group as well.

Given these relations between language and working memory and language and behavioral control, the current study investigated the association between language and cognitive control in early childhood. Language comprehension and WMIC were hypothesized to be positively associated at each age, as children with high WMIC skills were expected to have high receptive vocabularies. Further, recognizing that these abilities may be reciprocally related and children are improving in both of these abilities during the early years, the associations between the two cognitive constructs were expected to increase in strength with age. Finally, we hypothesized that language comprehension ability would explain a significant portion of variance in WMIC performance and perhaps even mask the influence of age.

3. Associated brain processes

In addition to associations with regulatory aspects of temperament and language, improvements on cognitive control tasks, including those requiring WMIC, have been associated with the development of the DL-PFC (Diamond, 2002; Diamond et al., 1997). There is strong evidence to link the functioning of the DL-PFC with this type of working memory in infants and primates, including much neuroscience work (Diamond, 1990a, 1990b; Diamond & Goldman-Rakic, 1989) and suggestive evidence from electroencephalographic (EEG) studies with infants (Bell, 2001, 2002; Bell & Fox, 1992, 1997) and young children (Wolfe & Bell, 2004; Wolfe & Bell, in press).

In previous WMIC studies with infants using a looking version of Piaget's A-not-B task, we showed that EEG power values increased from baseline-to-task at frontal as well as at posterior scalp regions for high performing infants at 8 months of age. Infants who demonstrated less developed WMIC skills showed no change in EEG power values from baseline-to-task (Bell, 2001, 2002). In more recent work, we showed a relation between scalp-recorded EEG and WMIC performance (as measured by the day–night and yes–no tasks) for that same group of 8-month-olds as they grew to early childhood. Specifically, at $4\frac{1}{2}$ years of age, there was an increase in EEG power from baseline-to-task for the medial frontal scalp locations only – a region that arguably represents prefrontal cortex activation. Again, this baseline-to-task increase in EEG power was found for the high performing children only. Low performing children showed no change in EEG power from baseline-to-task (Wolfe & Bell, 2004).

The findings from our previous work identified a couple of intriguing notions. First, these studies demonstrated that WMIC task performance was associated with differences in EEG power—and highlighted the value of EEG power from the frontal electrode sites for predicting WMIC task performance (Wolfe & Bell, 2004; Wolfe & Bell, *in press*). Second, the results of these studies suggested that change was occurring for the pattern of baseline-to-task EEG power from infancy to early childhood. Specifically, the pattern of EEG power in which one particular frontal scalp location increased in power from baseline-to-task for the $4\frac{1}{2}$ -year-olds was notably different than that found when the children were infants, in which multiple frontal and posterior scalp locations increased in power from baseline-to-task.

This increasing specificity of task-related EEG power seen when comparing our sample during infancy and early childhood, that is the increase in EEG power moving from diffuse-to-focal scalp locations (Bell & Wolfe, 2007), is comparable to fMRI investigations of developmental patterns of activation demonstrating increasing specificity of function with development (see Casey, Tottenham, Liston, & Durston, 2005, for a review). If there is, in fact, an increasing specificity of brain electrical activity between infancy and age $4\frac{1}{2}$ that can be captured with the EEG methodology, at what point between infancy and early childhood does this increase in specificity occur? Might it be occurring during a time of great advance in cognitive control? Thus, we sought to extend previous research with $4\frac{1}{2}$ -year-old children to include the $3\frac{1}{2}$ - and 4-year-old age groups to assess age-related differences in WMIC and the associated patterns of brain electrical activity as well as investigate the value of the medial frontal electrode sites in predicting WMIC performance for the two younger age groups.

4. Goal and hypotheses

In summary, the main goal of our study was to investigate age differences in WMIC performance for three age groups of children ($3\frac{1}{2}$ -, 4-, and $4\frac{1}{2}$ -year-olds) and to determine if these age differences were attributable to individual differences in temperament characteristics, linguistic abilities, and differences in brain electrical activity. We hypothesized that WMIC ability would increase across the three age groups, be related to the regulatory dimensions of temperament for each age group (i.e., positive relations – which would increase in strength across the ages – were expected for the effortful control dimensions, and negative associations were expected for the surgency dimensions), and be related to language comprehension – a relation that was also hypothesized to increase with age. Finally, we hypothesized that the patterns of WMIC task-related brain electrical activity would change from diffuse to more localized across these three age groups and that the medial frontal region would be related to WMIC performance at each age.

5. Method

5.1. Participants

Three groups of children – 20 3½-year-olds (41–43 months), 20 4-year-olds (47–49 months), and 21 4½-year-olds (53–55 months) – and their parents were recruited from the community for participation in this study. These age groups were chosen based both on Diamond's work showing notable advances in WMIC (e.g., [Diamond & Taylor, 1996](#)) and on [Gerardi-Caulton's work \(2000\)](#) demonstrating age-related differences in temperament-cognition relations at 6-month intervals across the early childhood years. Half of the children were male, and most were European Caucasian (85%), had one or two siblings (80%), and had attended preschool (90%). The average age for parents was 34 years, and the mean education level (in years) was over 16 both for mothers and fathers. All of the children were born after uncomplicated, full-term pregnancies and all children had experienced healthy development throughout childhood.

5.2. Procedures

Upon arrival at our research lab, participants and their parents were greeted, procedures were described, signed consent was obtained from the parents, and verbal assent was obtained from the children. A series of WMIC tasks that emphasize executive attention and inhibitory control was administered. The accompanying parent was seated beside and slightly behind the child throughout the visit.

5.3. Working memory and inhibitory control tasks

A series of five tasks was administered to assess WMIC abilities in the young children. All of the tasks required the children to pay attention to a given set of rules, remember the rules throughout the task, and to inhibit a dominant response tendency, which are the hallmarks of WMIC tasks. Two of the tasks were accomplished during the collection of EEG data as they did not require any gross motor movement from the child. The first two tasks, the goldfish task and the Simon-says task, were administered without electrophysiological recordings and served as “warm-up” exercises through which the children became more comfortable in the lab and with the experimenter.

5.3.1. Goldfish task

The goldfish task, also known as the tongue task, was taken from a battery of tasks to assess the effortful control abilities of young children ([Kochanska et al., 2000](#)). This task challenged the child to hold a goldfish cracker (or an M&M when extra motivation was needed) on his or her tongue without chewing it for increasing intervals of time (i.e., four trials with delays of 10, 20, 30, and 15 s). The nominal success of the child to delay chewing the cracker was coded (successful or unsuccessful). The final score was a percentage based on the number of successful trials (i.e., 4 successes = 100, 3 successes = 75, 2 successes = 50, 1 success = 25, and 0 successes = 0). This task was videotaped and later scored for accuracy of inhibitory performance. Interrater reliability was calculated for 20% of the sample and percentage of agreement on coding success to inhibit chewing the cracker was 90%. The total administration time for this task was approximately 3 min.

5.3.2. *Simon-says task*

The second “warm-up” task was a simplified version of the traditional Simon-says game and closely followed the Bear/Dragon procedure described by Carlson et al (2002; adopted from Reed, Pien, & Rothbart, 1984) except a pig puppet and a bull puppet were used. To begin, the experimenter asked the children to imitate the 10 target actions to confirm that the children could indeed perform these actions (e.g., stick out your tongue, touch your ears, clap your hands, etc.). The experimenter then introduced the two puppets. The first puppet was described as a “nice pig”, and the children were instructed, “So, when Pig talks to us, we will do what he tells us to do.” The pig trials were the activation trials. The second puppet was described as a “mean bull”, and the children were instructed, “So when Bull talks to us, we will not listen to him. If he tells us to do something, we will *not* do it.” The bull trials were the inhibition trials – the trials of particular interest in this study. Two practice trials followed, in which the experimenter moved the pig’s mouth and said (in a high-pitched voice), “Touch your nose,” and then moved the bull’s mouth and said (in a low, gruff voice), “Touch your ear.” Children passed the practice test if they followed the pig’s command but ignored the bull’s command. Difficulty passing the bull test trial (i.e., failing two practice trials) resulted in the assistance of a second experimenter (or the mother) to play the game with child and to remind the child to inhibit. Ten test trials followed (five pig trials and five bull trials, alternating order) in which children were given no assistance but were praised when the experimenter felt they needed encouragement. This task was videotaped and later scored for accuracy of inhibitory performance (i.e., the bull trials). The final score was a percentage based on the number of successful trials (i.e., 5 successes = 100, 4 successes = 80, 3 successes = 60, 2 successes = 40, 1 success = 20, 0 successes = 0). Interrater reliability was calculated for 20% of the sample and percentage agreement on coding success to inhibit performance on bull trials was 92%. The total administration time for this task was approximately three minutes.

5.3.3. *Day–night Stroop-like task*

The day–night Stroop-like task has been used in the developmental literature with children ages $3\frac{1}{2}$ to 7 years of age and is hypothesized to involve the functioning of the dorsolateral prefrontal cortex (Diamond et al., 1997; Diamond & Taylor, 1996; Gerstadt et al., 1994). One set of laminated cards (10 cm × 15 cm) was used. The children were instructed to say “day” when shown a card with a picture of the moon and stars and to say “night” when shown a card with a picture of the sun. The children were given two learning trials during which they were praised or corrected, and then 16 test trials were administered, eight with the sun card and eight with the moon card arranged in a pseudorandom order. The series of stimulus cards were presented as follows: D, N, N, D, N, N, D, D, D, N, D, N, N, D, D, and N. No feedback was given during testing. The total administration time for this task was approximately three minutes. The percentage correct was calculated. The percentage of agreement between two coders for 20% of the sample for the day–night task was 93%. Children were seated in a chair across from the experimenter, and EEG data were collected during this task.

5.3.4. *Yes–no task*

The yes–no task has been used in the developmental literature with $4\frac{1}{2}$ -year-old children and has been associated with increased EEG power in the medial frontal scalp locations (Wolfe & Bell, 2004). Modeled after the day–night testing procedure, the child was instructed to say “no” when the experimenter nods her head and to say “yes” when the experimenter shakes her head. Again, the children were given two learning trials during which they were praised or corrected, and then 16 test trials were administered, with eight head nods and eight head shakes arranged in

a pseudorandom order. The series of stimulus gestures was presented as follows: Y, N, N, Y, N, N, Y, Y, Y, N, Y, N, N, Y, Y, and N. No feedback was given during testing. The total administration time for this task was approximately 3 min. The percentage correct was calculated. The percentage of agreement between two coders for 20% of the sample for the yes–no task was 96%. Children remained seated in the chair across from the experimenter, and EEG data were collected during this task.

5.3.5. Dimensional Change Card Sort

The Dimensional Change Card Sort (DCCS) has been used in the developmental literature to assess executive function and rule use in young children (Zelazo, Frye, & Rapus, 1996; Zelazo et al., 2003), and arguably requires the skills of focused attention, working memory, and inhibitory control. One set of laminated cards (11 cm × 7 cm) was used. There were two target cards (i.e., a blue car and a red flower) to be matched to a series of 10 test cards that displayed the same shape but colors opposite of the target cards (i.e., red cars and blue flowers). The children were first instructed to sort five test cards by color (pre-switch condition) and then were instructed to switch and to sort the remaining five test cards by shape (post-switch condition). The dimension (i.e., color or shape) that was relevant during the pre-switch phase was counterbalanced across participants within each age group. In the post-switch condition, the child was reminded of the rule after each trial. However, the child was not told whether or not she sorted the cards correctly; the experimenter simply said, “Okay”, and began the next trial. The percentage correct of post-switch sorts was used in these analyses. Interrater reliability was calculated for the post-switch trials for 20% of the sample and percentage agreement on coding success to sort correctly was 92%. The total administration time of this task was approximately 7 min.

5.4. EEG

EEG measures were accomplished during a 2-min, eyes-open baseline period and during two WMIC tasks, the Stroop-like day–night task and the yes–no task. The baseline data were collected as the children watched an animated video-clip. EEG electrodes were applied as the child was entertained by a research assistant and an age appropriate computer game.

EEG was recorded using an Electro-Cap from eight left and eight right scalp sites: Frontal pole (Fp1, Fp2), medial frontal (F3, F4), lateral frontal (F7, F8), central (C3, C4), anterior temporal (T3, T4), posterior temporal (T7, T8), parietal (P3, P4), and occipital (O1, O2), referenced to Cz. NuPrep and EEG Gel conductor were inserted into each recording site and the scalp lightly rubbed. Electrode impedances were measured and were accepted if they were below 10 k Ω . The electrical activity from each lead was amplified using separate SA Instrumentation Bioamps, band passed from .1 Hz to 100 Hz, and digitized online at 512 samples per second to prevent aliasing. Activity for each lead was displayed on a Pentium computer using SnapMaster acquisition software.

The EEG data were examined and analyzed using software developed by James Long Company (Canoga Lake, NY). First, the data were rereferenced via software to an average reference configuration and then artifact scored for eye blinks (using Fp1 and Fp2 as a guide) and gross motor and muscle movements through visual examination. Slightly more than 40% of the EEG data – including both baseline (43%) and task (45%) epochs – was artifact-rejected and was eliminated from all subsequent analyses. These percentages of artifact-rejected data are comparable to those found in previous EEG research with preschool children (Wolfe & Bell, 2004). The amount of data remaining in the analyses (i.e., artifact-free data) was unrelated to all CBQ temperament dimensions except shyness; shyness was negatively related to the amount of baseline and task

artifact-free EEG data (baseline $r = -.28$, $p = .06$; task $r = -.32$, $p = .04$). These negative relations suggest that shy children contributed less artifact-free data than children who were rated less shy by their parents. The artifact-free data were analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1-s width and 50% overlap. Power was computed for the 6–10-Hz frequency band, the dominant frequency for preschool children (Marshall, Bar-Haim, & Fox, 2002) and a bandwidth that has shown associations with individual differences in cognitive processing with this age population (Wolfe & Bell, 2004). The power was expressed as mean square microvolts, and the data transformed using the natural log (ln) to normalize the distribution.

5.5. Temperament assessment

The CBQ (Rothbart et al., 2001) was used to examine parent perceptions of child temperament. The CBQ is a 196-item questionnaire designed to measure general patterns of behavior in children ages 3–7 years of age. Reliability estimates for the 15 CBQ scales for 4- and 5-year-olds ratings range from .64 to .92, with a mean of .73. Three higher order factors are consistently yielded with this instrument: effortful control (EC), surgency (SU), and negative affectivity (NA). The questionnaire was mailed to the parents in advance and was collected at the laboratory visit. Although all CBQ temperament scales were collected, the scales of particular interest to the current study are the regulatory aspects of temperament that are associated with the EC and SU factors.

5.6. Language assessment

The final segment of the visit consisted of a language assessment. Specifically, the Peabody Picture Vocabulary Test (PPVT-III; Dunn & Dunn, 1997) was administered to the children to examine receptive vocabulary and verbal comprehension. The PPVT-III is a nationally standardized instrument. However, because age differences were the focus of the current investigation, the children's raw scores were used in all analyses.

6. Results

There was a reduction in sample size due to some children refusing to participate in the WMIC tasks (two children at age $3\frac{1}{2}$, three children at age 4, and two children at age $4\frac{1}{2}$). These children were eliminated from the subsequent analyses. The children who chose not to participate in the WMIC tasks differed from those children who agreed to participate in the tasks on parent ratings of high intensity pleasure, $F(1, 57) = 4.07$, $p = .05$, and perceptual sensitivity, $F(1, 57) = 4.01$, $p = .05$. Compared to those children who chose to not participate in the WMIC tasks, those children who participated had higher parental ratings of high intensity pleasure (participated $M = 4.93$, $S.D. = .96$; did not participate $M = 4.05$, $S.D. = 1.49$) and lower ratings of perceptual sensitivity (participated $M = 5.13$, $S.D. = .68$; did not participate $M = 5.70$, $S.D. = .33$); suggesting that those children who participated were more likely to enjoy situations involving high stimulus rate and complexity and were less sensitive to slight, low-intensity stimuli from the environment than those children who did not participate. Those children who did not participate did not differ from those children who agreed to participate on any other variable of interest (i.e., temperament scales or language comprehension scores), all $F_s < 1.97$ and all $p_s > .17$.

Pearson correlations were calculated for all possible WMIC task pairs to determine the degree of association among the measures. As shown in Table 1, all WMIC measures were significantly,

Table 1
Pearson correlations among the five WMIC tasks

| | GF | SS | DN | YN |
|-------------------------------------|-------|-------|-------|-------|
| Goldfish task (GF) | – | | | |
| Simon-says task (SS) | .39** | – | | |
| Day–night task (DN) | .33** | .50** | – | |
| Yes–no task (YN) | .37** | .53** | .60** | – |
| Dimensional Change Card Sort (DCCS) | .29* | .55** | .65** | .57** |

Note. $n = 54$.

* $p < .05$.

** $p < .01$.

positively correlated. Thus, due to the statistical and conceptual relations among the WMIC measures, a composite score that averaged the percentages correct for all five WMIC task scores was created (i.e., WMIC₅) to address the hypotheses of general WMIC functioning.

6.1. Age differences

Table 2 displays the means and standard deviations for each WMIC measure and for the composite WMIC₅ score by age group. An ANOVA was performed with age as the independent variable and the WMIC₅ score as the dependent variable. The results of this analysis revealed a difference between the age groups for the WMIC₅ score, $F(2, 52) = 4.08$, $p = .02$. The results of a Bonferroni post-hoc analysis revealed a difference between scores of the 3½- and the 4½-year-old age groups ($M_d = 23.19$, S.E. = 8.19, $p = .02$). The differences shown between the 3½- and 4-year-olds as well as the 4 and 4½-year-olds were not significant (both $M_{ds} < 17.61$ and $ps > .17$), although they were in the hypothesized direction.

6.2. Regulatory dimensions of temperament

To investigate the associations between temperament and WMIC for each age group, Pearson correlations were calculated between the WMIC tasks and the regulatory dimensions of temperament, which included the EC and SU factors of the CBQ and their respective subscales. As expected, associations were found between the WMIC measures and the regulatory temperament dimensions. However, rather than finding the hypothesized, systematic relations between WMIC measures and the temperament dimensions for each age group, the nature of the associations was different for each age group. Specifically, as shown in Table 3, a cluster of positive associations

Table 2
Means and standard deviations for the WMIC tasks by age

| | 3½ years ($n = 18$) | 4 years ($n = 17$) | 4½ years ($n = 19$) |
|-------------------|-----------------------|----------------------|-----------------------|
| Goldfish | 75.91 (39.30) | 87.06 (30.16) | 93.86 (14.91) |
| Simon-says | 59.72 (43.36) | 73.53 (42.82) | 92.63 (24.23) |
| Day–night | 61.80 (34.96) | 74.26 (25.18) | 77.96 (21.68) |
| Yes–no task | 42.36 (31.98) | 60.66 (37.03) | 66.44 (31.40) |
| DCCS | 61.39 (44.91) | 79.00 (39.04) | 86.23 (31.35) |
| WMIC ₅ | 60.23 (27.66) | 74.90 (25.20) | 83.42 (21.65) |

Table 3

Pearson correlations between the WMIC tasks and the CBQ factors and scales

| | GF | SS | DN | YN | DCCS | WMIC ₅ |
|------------------------|-------|-------|-------|-------|--------|-------------------|
| Age 3½ (n = 18) | | | | | | |
| EC | .07 | .50* | .47* | .14 | .07 | .33+ |
| Inhibitory control | −.01 | .36+ | .32+ | .09 | .01 | .15 |
| Attention focusing | .02 | .38+ | .45* | .24 | .20 | .40* |
| Low pleasure | .20 | .63** | .53* | .28 | .09 | .43* |
| Perceptual sensitivity | .08 | .22 | .12 | −.23 | −.15 | .02 |
| SU | .18 | .00 | .06 | −.25 | −.19 | −.02 |
| Impulsivity | .23 | −.01 | −.04 | −.15 | −.18 | −.03 |
| Activity level | −.12 | .09 | .07 | −.06 | .31 | .10 |
| Approach | .09 | −.09 | −.08 | −.31 | −.24 | −.22 |
| High pleasure | .13 | .09 | .02 | −.30 | −.354+ | −.09 |
| Age 4 (n = 17) | | | | | | |
| EC | .15 | .51* | .22 | .34+ | .40+ | .48* |
| Inhibitory control | .29 | .42* | .24 | .33+ | .46* | .50* |
| Attention focusing | −.05 | .63** | .18 | .29 | .16 | .37+ |
| Low pleasure | .11 | .41* | .27 | .24 | .34+ | .40+ |
| Perceptual sensitivity | .13 | −.15 | −.12 | .07 | .24 | .05 |
| SU | .27 | −.06 | −.07 | .08 | −.04 | .04 |
| Impulsivity | .33+ | −.22 | −.28 | −.03 | −.32 | −.16 |
| Activity level | −.17 | −.07 | −.12 | −.08 | −.24 | −.19 |
| Approach | −.03 | −.29 | −.05 | .16 | −.26 | −.15 |
| High pleasure | .03 | −.10 | .09 | .00 | .17 | .04 |
| Age 4½ (n = 19) | | | | | | |
| EC | −.30 | −.13 | −.05 | .15 | −.07 | −.04 |
| Inhibitory control | .18 | .12 | .23 | .51* | .12 | .32+ |
| Attention focusing | −.32+ | −.12 | −.05 | −.17 | .04 | −.13 |
| Low pleasure | −.04 | .01 | .08 | .00 | .03 | .02 |
| Perceptual sensitivity | −.47* | −.28 | −.30 | .08 | −.30 | −.23 |
| SU | −.49* | −.35+ | −.43* | −.13 | −.31 | −.35+ |
| Impulsivity | −.39+ | −.35+ | −.42* | −.33+ | −.32+ | −.41* |
| Activity level | −.35+ | −.20 | −.37+ | .05 | −.20 | −.20 |
| Approach | −.32+ | −.16 | −.08 | .20 | −.11 | −.05 |
| High pleasure | −.44* | −.42* | −.51* | −.27 | −.40* | −.45* |

Note—EC: effortful control; SU: surgency; GF: goldfish task; SS: Simon-says task; DN: day–night task; YN: yes–no task; DCCS: Dimensional Change Card Sort task; WMIC₅: average score of five tasks.

+ $p \leq .10$.

* $p \leq .05$.

** $p \leq .01$.

was found between the WMIC tasks and the EC scales for the 3½- and 4-year age groups, while a cluster of negative associations was found between the WMIC tasks and the SU scales for the 4½-year age group. We expected WMIC and EC to be positively related for each age group and to increase in association strength with age. An inspection of the WMIC₅ and EC correlations for the 3½- and 4-year age groups provided partial support for this hypothesis, as the correlation was .33 at age 3½ and .48 at age 4; however, the difference between these two correlations was not statistically significant, $z = .20$, $p = .42$.

6.3. Language

Pearson correlations were calculated between the WMIC₅ scores and the PPVT raw scores for each age group. Language comprehension was a meaningful associate of WMIC performance at all ages (age 3½: $r = .51$, $p = .02$; age 4: $r = .55$, $p = .01$; age 4½: $r = .78$, $p < .001$). Although, the association strengths appeared to increase with age as hypothesized, none of the pairwise comparisons were significant (all z s < 1.34 and all p s $> .09$).

6.4. Explanation of variance: age, temperament, and language

To determine the amount of variance explained in WMIC performance by age, the regulatory dimensions of temperament, and language comprehension, a series of hierarchical regressions was performed. The first regression included age as the independent, predictor variable (by the creation of two dummy variables) and the WMIC₅ score as the dependent variable. Consistent with the results of the above ANOVA for age and WMIC performance, this analysis indicated that the age variable accounted for 19% of the variance in WMIC performance with these data (see Table 4, step 1).

To determine the amount of variance explained in WMIC performance by the regulatory dimensions of temperament above and beyond age, two regressions were performed with the WMIC₅ score as the dependent variable. The first analysis included age as the first independent variable and EC as the second independent variable, and the second analysis included age, EC, and

Table 4
Summary of regression procedure investigating age, effortful control, surgency, and language as predictors of WMIC

| | df1 | df2 | Beta | <i>t</i> | Sig. | <i>R</i> | <i>R</i> ² | <i>R</i> ² change | <i>F</i> change | Sig. |
|--|-----|-----|-------|----------|------|----------|-----------------------|------------------------------|-----------------|------|
| Step 1: Age ^a | | | | | | | | | | |
| Model 1 | | | | | | | | | | |
| Age D1 | 2 | 50 | -.50 | -3.39 | .00 | .43 | .19 | .19 | 5.78 | .01 |
| Age D2 | | | -.22 | -1.50 | .14 | | | | | |
| Step 2: Age and EC ^a | | | | | | | | | | |
| Model 2 | | | | | | | | | | |
| Age D1 | 1 | 49 | -.50 | -3.56 | .00 | .51 | .26 | .07 | 4.92 | .03 |
| Age D2 | | | -.21 | -1.51 | .14 | | | | | |
| CBQ (EC) | | | .27 | 2.22 | .03 | | | | | |
| Step 3: Age, EC, and SU ^a | | | | | | | | | | |
| Model 2 | | | | | | | | | | |
| Age D1 | 1 | 48 | -.50 | -3.53 | .00 | .51 | .26 | .00 | .04 | .85 |
| Age D2 | | | -.22 | -1.51 | .14 | | | | | |
| CBQ (EC) | | | .27 | 2.16 | .04 | | | | | |
| CBQ (SU) | | | -.02 | -.19 | .85 | | | | | |
| Step 4: Age, EC, SU, and PPVT ^a | | | | | | | | | | |
| Model 3 | | | | | | | | | | |
| Age D1 | 1 | 47 | -.252 | -1.81 | .08 | .45 | .39 | .19 | 16.32 | .00 |
| Age D2 | | | -.037 | -.28 | .78 | | | | | |
| CBQ (EC) | | | .145 | 1.28 | .21 | | | | | |
| CBQ (SU) | | | 1.279 | .45 | .66 | | | | | |
| PPVT | | | .512 | 4.04 | .00 | | | | | |

^a Indicates that overall model is significant.

SU as the first, second, and third independent variables, respectively. The results of these analyses revealed a significant contribution from EC to the explanation of variance in WMIC performance above and beyond age, with both variables (i.e., age and EC) accounting for 26% of the variance in WMIC. The SU factor did not contribute unique variance (see Table 4, steps 2 and 3).

Finally, a regression was performed with the WMIC₅ score as the dependent variable and with age, EC, SU, and language comprehension included as the first, second, third, and fourth independent variables, respectively. All models were significant, with the final model (including all variables) explaining 39% of the variance in WMIC performance. With the inclusion of the language comprehension measure in the final model, however, the other variables were diminished in their contribution to WMIC performance—although age retained a marginally significant contribution (see Table 4).

6.5. Brain electrical activity

Due to some children refusing the EEG equipment, the sample size was further reduced. Specifically, nine 3½-year-olds, four 4-year-olds, and two 4½-year-olds did not contribute EEG data (the children either did not agree to wear the EEG electrode cap or to the application of gels). To determine if these children differed from those children who accepted the EEG equipment on WMIC ability, ANOVAs were conducted with EEG participation (accepted or rejected) as the independent variable and WMIC₅ as the dependent variable. Due to the disproportionately large number of 3-year-olds that rejected the EEG equipment, ANOVAs were conducted separately for each age. A significant difference was found for the 3½-year-old age group, $F(1, 16) = 8.95, p < .01$, as those children who accepted the EEG equipment had higher scores on the WMIC measures than those children who did not accept the equipment (accepted $M = 71.62$, S.D. = 17.80; rejected $M = 37.47$, S.D. = 31.17). For the 4- and 4½-year-old age groups, there were no differences between those children who accepted or rejected the EEG equipment on WMIC performance, both F s < .23 and both p s > .64.

Similar analyses were performed for temperament and language to determine if the children who rejected the EEG equipment were different from the children who accepted it. With regard to temperament, there was a marginally significant relation found in the youngest age group but no differences found in the two older age groups. Specifically, at age 3½, a marginally significant difference was found for parental ratings of shyness, $F(1, 18) = 3.27, p = .08$, as those children who accepted the EEG equipment were rated lower on the shyness scale than those children who rejected the equipment (accepted $M = 2.95$, S.D. = .92; rejected $M = 3.92$, S.D. = 1.45). At age 4, there was a significant difference in language ability between those children who accepted and those who rejected the EEG equipment, $F(1, 18) = 4.25, p = .05$ (accepted $M = 64.88$, S.D. = 10.76; rejected $M = 53.50$, S.D. = 2.52). There were no other differences found for language or the temperament scales of interest, all F s < 2.57 and all p s > .13. The subsequent analyses were performed on 11 3½-year-old children, 16 4-year-old children, and 19 4½-year-old children.

To investigate how age-related differences in WMIC might be associated with differences in brain electrical activity, two sets of analyses were performed. The first set of analyses addressed the increasing specificity hypothesis, and the second set addressed the association between individual differences in WMIC performance and brain electrical activity from the frontal scalp locations.

6.5.1. Increasing specificity hypothesis

To investigate how age-related differences in WMIC might be related with differences in patterns of brain electrical activity, a series of analyses was conducted using the baseline- and

Table 5

Summary of multivariate analyses F values for age comparisons by the frontal pole, medial frontal, anterior temporal, and posterior temporal regions

| | d.f. | Fp1/Fp2 | F3/F4 | T3/T4 | T7/T8 |
|------------------------|------|---------|--------|--------|--------|
| Age 3½ | | | | | |
| Condition | 1,10 | .28 | .16 | .36 | .86 |
| Hemisphere | 1,10 | 3.21 | 3.34 | 10.61* | 2.22 |
| Condition × hemisphere | 1,10 | 3.64 | .99 | .12 | .98 |
| Age 4 | | | | | |
| Condition | 1,15 | 17.03* | 10.45* | 20.11* | 27.98* |
| Hemisphere | 1,15 | .40 | .01 | 2.36 | .11 |
| Condition × hemisphere | 1,15 | 1.04 | .22 | 1.03 | 1.75 |
| Age 4½ | | | | | |
| Condition | 1,18 | 10.18* | 12.06* | 4.77 | 10.82* |
| Hemisphere | 1,18 | .21 | 1.71 | .04 | .01 |
| Condition × hemisphere | 1,18 | 6.82 | 9.90* | 1.18 | 1.04 |

* $p \leq .01$.

task-related EEG power values. The task-related EEG data were collected during the day–night and the yes–no tasks. A repeated-measures MANOVA was performed on the \ln (6–10 Hz) EEG power values at each age (3½, 4, and 4½ years) for each scalp region that had shown a baseline-to-task increase in EEG power (i.e., a condition by region interaction) in a preliminary MANOVA, $F(7, 37) = 3.82, p = .003$ (i.e., frontal pole, medial frontal, anterior temporal, and posterior temporal). The within-subjects factors for the age by region analyses were condition (i.e., baseline and task) and hemisphere (i.e., left and right). Because we were performing multiple MANOVAS, the adjusted p value was $\leq .01$ (4 regions = 4 analyses; $p = .05/4 = .0125$). F -values for each analysis can be found in Table 5.

6.5.2. Frontal pole (Fp1/Fp2)

As shown in Fig. 1, there were main effects for condition at ages 4 and 4½, with greater power values during the tasks than during baseline for both age groups.

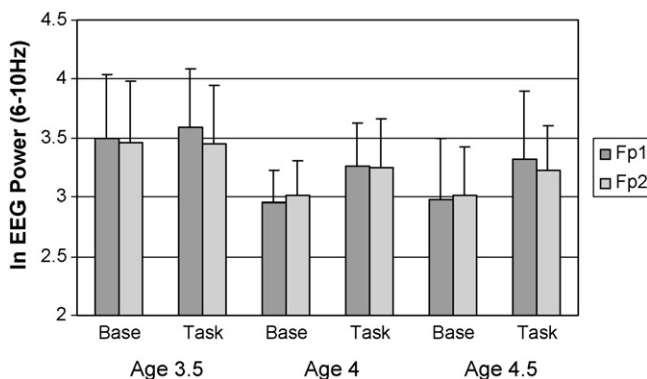


Fig. 1. Baseline and task EEG power values (\ln 6–10 Hz) from frontal pole (Fp1/Fp2) scalp locations for the three age groups. There is an increase in baseline-to-task \ln EEG power at age 4 and age 4½.

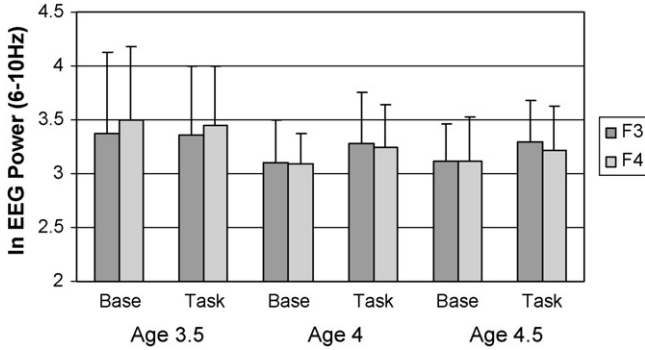


Fig. 2. Baseline and task EEG power values (ln 6–10 Hz) from medial frontal (F3/F4) scalp locations for the three age groups. There is an increase in baseline-to-task ln EEG power at age 4, and at age 4½ there is an interaction between condition and hemisphere, such that left medial frontal region (F3) power increases from baseline-to-task relative to the right medial frontal region.

6.5.3. *Medial frontal (F3/F4)*

As shown in Fig. 2, there were main effects for condition at ages 4 and 4½, with greater power values during the tasks than during baseline for these age groups. At age 4½, however, this effect was superseded by a condition by hemisphere interaction, with the left medial frontal region displaying a baseline-to-task increase in power relative to the right medial frontal region.

6.5.4. *Anterior temporal (T3/T4)*

As shown in Fig. 3, there was a main effect for condition at ages 3½ and 4. At 3½, power values decreased from baseline-to-task, whereas there were greater power values during the tasks than during baseline at age 4.

6.5.5. *Posterior temporal (T7/T8)*

As shown in Fig. 4, there was a main effect for condition at age 4 and age 4½, with greater power values during the tasks than during baseline for both age groups.

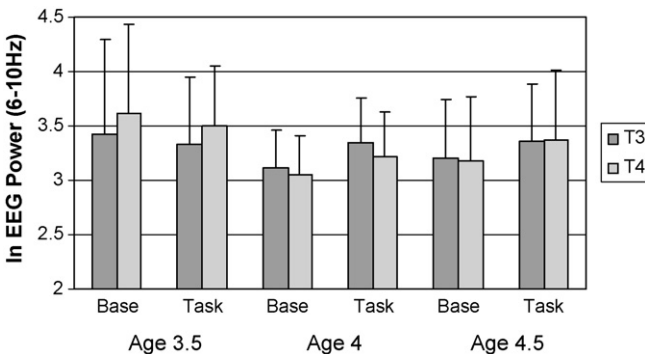


Fig. 3. Baseline and task EEG power values (ln 6–10 Hz) from anterior temporal (T3/T4) scalp locations for the three age groups. There is an increase in baseline-to-task ln EEG power at age 4 only, as well as a decrease in baseline-to-task ln EEG power at age 3½.

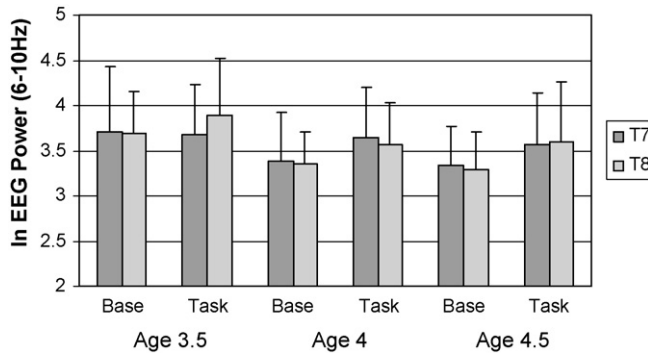


Fig. 4. Baseline and task EEG power values (ln 6–10 Hz) from posterior temporal (T7/T8) scalp locations for the three age groups. There is an increase in baseline-to-task ln EEG power at age 4 and age $4\frac{1}{2}$.

To summarize, there were increases in baseline-to-task EEG power for four regions in the 4-year-olds (i.e., frontal pole, medial frontal, anterior temporal, and posterior temporal) and increases in baseline-to-task power for three regions in the $4\frac{1}{2}$ -year-olds (i.e., frontal pole, medial frontal, and posterior temporal). There was a decrease in baseline-to-task EEG power at anterior temporal for the $3\frac{1}{2}$ -year-olds.

6.5.6. WMIC task performance and EEG power

To investigate the predictive value of task-related EEG power from the region yielding predictive value on WMIC performance in our previous research (i.e., medial frontal; Wolfe & Bell, 2004; Wolfe & Bell, *in press*), a regression analysis was performed with the left and right medial-frontal EEG power values (i.e., F3 and F4, respectively) as independent variables and WMIC₂ as the dependent variable. WMIC₂ was a composite score created by averaging the day–night and yes–no task performances (percentages correct); these were the two tasks administered during EEG data collection as the other three WMIC tasks required gross motor movements by the child. This analysis was performed separately for each age group. The results of these analyses partially supported our previous work and current hypotheses. The model yielded for the 4-year-old data was significant, $F(2, 13) = 4.73, p = .03$, and the model for the $3\frac{1}{2}$ -year-old data was marginally so, $F(2, 8) = 3.53, p = .08$; the beta coefficients for the left and right medial-frontal scalp locations were significant at age $3\frac{1}{2}$ and age 4. These findings suggest that the left and right medial frontal regions are valuable for explaining variance in WMIC performance. However, as shown in Table 6, for the $4\frac{1}{2}$ -year-old data the model for the EEG power values from the left and right scalp locations was not significant, $F(2, 16) = .54, p = .59$.

Given the hypothesized diffuse-to-focal changes in patterns of brain electrical activity across the early childhood years, an additional analysis was performed to evaluate the contribution of EEG power from additional electrode sites in predicting WMIC performance. A backward regression analysis was performed with the EEG power values from the brain regions that yielded significant associations in the previous increasing specificity investigation, specifically the frontal pole, medial frontal, anterior temporal, and posterior temporal regions. This analysis was performed separately for each age group. The results of these analyses yielded significant final models for the data at age $3\frac{1}{2}$, $F(4, 6) = 5.53, p = .03$, and at age 4, $F(2, 13) = 5.10, p = .02$, but not at age $4\frac{1}{2}$, $F(2, 16) = 2.33, p = .13$. At age $3\frac{1}{2}$, the scalp locations that emerged as valuable were left frontal pole (Fp1), left medial frontal (F3), and left and right anterior temporal (T3 and T4, respectively). At

Table 6

Summary of regression analyses investigating left and right medial frontal EEG power as predictors of WMIC performance by age

| | df1 | df2 | Beta | <i>t</i> | Sig. | <i>R</i> | <i>R</i> ² | <i>F</i> change | Sig. |
|---------------------------|-----|-----|-------|----------|------|----------|-----------------------|-----------------|------|
| Age 3½ | | | | | | | | | |
| Left medial frontal (F3) | 2 | 8 | 2.21 | 2.64 | .03 | .69 | .47 | 3.53 | .08 |
| Right medial frontal (F4) | | | −2.02 | −2.41 | .04 | | | | |
| Age 4 | | | | | | | | | |
| Left medial frontal (F3) | 2 | 13 | −1.15 | −2.25 | .04 | .65 | .42 | 4.73 | .03 |
| Right medial frontal (F4) | | | 1.50 | 2.91 | .01 | | | | |
| Age 4½ | | | | | | | | | |
| Left medial frontal (F3) | 2 | 16 | .47 | .76 | .46 | .25 | .06 | .54 | .59 |
| Right medial frontal (F4) | | | −.26 | −.42 | .68 | | | | |

Table 7

Final models yielded from regression analyses investigating EEG power from multiple electrodes as predictors of WMIC performance

| | df1 | df2 | Beta | <i>t</i> | Sig. | <i>R</i> | <i>R</i> ² |
|------------------------------|-----|-----|-------|----------|------|----------|-----------------------|
| Age 3½ ^a | | | | | | | |
| Left frontal pole (Fp1) | 1 | 5 | −1.06 | −2.42 | .05 | .89 | .79 |
| Left medial frontal (F3) | | | 1.80 | 3.30 | .02 | | |
| Left anterior temporal (T3) | | | 2.43 | 2.87 | .03 | | |
| Right anterior temporal (T4) | | | −3.17 | −4.10 | .01 | | |
| Age 4 ^a | | | | | | | |
| Right frontal pole (Fp2) | 1 | 12 | −.89 | −2.37 | .03 | .66 | .44 |
| Right medial frontal (F4) | | | 1.18 | 3.16 | .01 | | |
| Age 4½ | | | | | | | |
| Right frontal pole (Fp2) | 1 | 15 | −.87 | −1.85 | .08 | .48 | .23 |
| Right anterior temporal (T4) | | | 1.01 | 2.16 | .05 | | |

^a Indicates that the overall model is significant.

age 4, the valuable locations were right frontal pole (Fp2) and right medial frontal (F4). Although not significant, the final model for the data at age 4½ included, as shown in Table 7, the right frontal pole (Fp2) and the right anterior temporal (T4) scalp locations.

7. Discussion

The purpose of our study was to investigate age variations in WMIC and how these differences were associated with variability in temperament, language comprehension, and brain electrical activity. The results demonstrated an increase in WMIC ability during early childhood, differential temperament-cognition relations for the three age groups, an indubitable association between WMIC and language comprehension, and different patterns of task-related brain electrical activity and different scalp locations (albeit all anterior locations) as predictors of WMIC performance for each age group.

7.1. Temperament and WMIC

We hypothesized that dimensions of temperament associated with the regulation of attention, emotion, and behavior in general would be related to effortful, controlled cognitive processing. Specifically, we expected positive associations between WMIC performance and EC and further proposed that these associations would increase in strength across the age groups. For the surgency factor, we hypothesized negative relations with the WMIC measures. These hypotheses were partially supported. Specifically, the correlations between the WMIC composite score (i.e., WMIC₅) and the higher order effortful control factor were .33 and .48 for the 3½- and 4-year-olds, respectively. Although the correlation for the 3½-year-olds was only marginally significant, the strength and direction of this association moved in the hypothesized direction. An inspection of the inhibitory control and attention focusing subscales of the effortful control factor revealed them to be significantly associated with the composite WMIC score. Obviously, these associations between the composite factors (i.e., WMIC₅ and effortful control) reflected the general pattern associations between the individual WMIC scores and the effortful control subscales for the 3½- and 4-year-olds—a clustering of positive associations. However, it was clear that only three scales of the effortful control factor (i.e., inhibitory control, attention focusing, and low-intensity pleasure) contributed to these relations. Hypothesized negative correlations between WMIC₅ and SU were non-existent for these two age groups.

The pattern of associations was much different for the 4½-year-olds. This group did not show the anticipated relation between WMIC performance and caregiver ratings of effortful control, although there was a rather strong correlation between the inhibitory control scale of the CBQ and the yes–no task of the WMIC battery. On the other hand, there was a clustering of negative associations between performance on the WMIC tasks and the scales that comprise the surgency factor, some significant and some marginally so. Notably, the association between WMIC₅ and surgency was only marginally significant, yet in the hypothesized direction, and significant negative associations were found for the composite WMIC measure and the impulsivity and high pleasure scales of the surgency factor.

It is intriguing that different temperamental styles were associated with WMIC performance at these different ages, ages that were separated by only a few months. These differential age findings are reminiscent of Gerardi-Caulton's (2000) work with 2½- and 3-year-olds, as she found differential age relations between temperament and performance on a cognitive control task. Gerardi-Caulton found positive associations between cognitive control and all four scales of the EC factor at age 2½; but for 3-year-old children, performance on this task was associated with only one scale from this factor, as well as a negative relation with anger/frustration scale. In a similar fashion, our previous research with 4½-year-olds demonstrated positive associations between WMIC performance and two scales of the EC factor (i.e., inhibitory control and attention focusing), as well as a robust negative relation with the positive approach scale of the surgency factor as well as the anger/frustration scale (Wolfe & Bell, 2004). Finally, work by Davis et al. (2002) with 6-year-old children indicated a positive association between controlled cognitive processing and the inhibitory control scale of the CBQ (i.e., not the higher order EC factor as hypothesized) and showed more robust relations from the SU factor and the impulsivity scale in particular.

It seems then that there is a trend for cognitive control to be positively associated with EC during the early years and then over time, perhaps as other cognitive functions (e.g., executive attention) are developing and “taking over”, there is less of a need for effortful control of behavior during cognitive tasks. Thus, the older preschool child is at a disadvantage for performance on

cognitive control tasks only when they are surgent or impulsive in their behavioral style, although the EC subscale of inhibitory control appears to maintain its value in predicting cognitive control performance across most studies. Rothbart, Ellis, and Posner (2004) arrived at a similar conclusion. Specifically, they report on work from their own lab finding age differences in the temperament-cognition relation in which volitional skills showed positive relations with caregiver-reported EC at 24 months and negative associations with impulsivity and SU at 30 months. They suggest that emerging self-regulation in the early years has a critical role in the development of volitional skills. Early self-regulatory skills may allow a child greater control as she waits or searches for appropriate opportunities to act, resists distractions, detects and corrects errors, overcome obstacles, and completes a goal. It may be that as these developing skills become more practiced with age, self-regulation may play a lesser role in the control of behavior (Rothbart et al., 2004).

These age-related association differences might also be considered in light of task difficulty or the age appropriateness of the tasks employed. For example, for our study, the goldfish task was arguably less age-appropriate for the $4\frac{1}{2}$ -year-olds than for the $3\frac{1}{2}$ - or 4-year-olds, particularly it was too easy for them. The goldfish task, or the tongue task, was originally intended for use with 33-month-olds (e.g., Kochanska et al., 2001). So, on the average a $4\frac{1}{2}$ year old should be able to successfully perform this task, unless of course they are surgent in their behavioral style. Likewise, the Simon-says task is best suited for the $3\frac{1}{2}$ - and 4-year-old children, yet requires a fair amount of EC and executive attention as the children need to inhibit themselves from performing a verbally commanded behavior. This task has been used in the developmental literature with children between the ages of 40 and 49 months (Reed et al., 1984), and most of the $4\frac{1}{2}$ -year-olds in our sample performed significantly above chance levels. So, by age $4\frac{1}{2}$ successful performance on this task is anticipated, unless of course, one has a surgent behavioral style. This theorizing is somewhat maintained when reflecting on the other tasks included in this study. Specifically, the yes–no and DCCS tasks could be considered too cognitively challenging for the $3\frac{1}{2}$ -year-olds, and thus no amount of EC would be beneficial. Yet, these tasks are within reach for the 4-year-old age group, and EC skills are advantageous. This assertion is further supported by the fact there is a positive association between parental ratings of inhibitory control and the yes–no task (i.e., the most difficult WMIC task) for the $4\frac{1}{2}$ -year-old group.

Although intriguing, these associations do not reveal any causal information. To elaborate on the previous age-related differences assertion and to speculate about the causal relations, three explanations are viable: Either temperament influences cognitive control, cognitive control influences temperament, or a third variable influences both control dimensions. From a temperament-influences-cognition perspective, perhaps those $3\frac{1}{2}$ - and 4-year-olds whose behavioral styles include high EC are at an advantage for cognitive processing, especially when it involves a frontally-associated, attentional control component. From a cognition-influences-temperament perspective, perhaps the $3\frac{1}{2}$ - and 4-year-olds included in this dataset are actually ahead of their time with regard to cognitive control abilities, and this precociousness facilitates self-regulation. At age $4\frac{1}{2}$, on the other hand, cognitive functioning that includes working memory, voluntary attention, and inhibitory control should be relatively developed and performance should be relatively high regardless of self-regulatory abilities. A temperament-influences-cognition perspective might suggest, then, that if one has a very surgent, impulsive behavioral style at age $4\frac{1}{2}$, then performance on this type of cognitive task will be impaired. A cognition-influences-temperament perspective would purport that some $4\frac{1}{2}$ -year-olds are at a disadvantage with regard to cognitive processing and frontal functioning, and this cognitive difficulty impairs their ability to regulate their surgent and impulsive behaviors. These propositions are largely based on the construct of attention and question the allocation of cognitive resources for WMIC ability. Finally, there could

be a third factor that is related and that may be influencing in the development of both of these control dimensions, such as language (Kopp, 1982) or caregiver interaction style and subsequent attention skill development (Bell & Wolfe, 2004).

7.2. *Language comprehension and WMIC*

As hypothesized, language comprehension was related to WMIC, and this association tended to increase in strength for each age group. Further, when the language comprehension measure was included in the hierarchical regression with the other variables of interest (i.e., age and EC), 39% of the variance in WMIC performance was explained but the language measure was the only one to retain a significant association with WMIC performance masking the effects of EC and marginalizing the contribution of age.

Given the age of this sample, this association may support Gathercole and Baddeley's work that suggests working memory capacity facilitates word learning. Those children with the greatest ability to focus attention, maintain task-relevant information, and execute the appropriate response in the face of competing information also had the highest scores on the language comprehension measure. On the other hand, supporting Luria's verbal control of behavior theory, perhaps good vocabulary skills allowed for good performance on a cognitive control task in which verbal instructions were given. Further, it is conceivable that the more words one knows, the better one can self-regulate and navigate the situation, control attention, and think through problems using private-speech or self-talk. Again, there could be a third variable influencing both performance on the WMIC tasks and vocabulary knowledge. For example, the parents could be contributing to the individual differences in WMIC and language. Certainly, parents influence the development of WMIC and the functioning of the prefrontal cortex through biological and environmental means including the experiences they provide for their children, and the way they perceive and interact with their children as independent thinkers (Landry, Smith, Swank, & Miller-Loncar, 2000). Similarly, parents influence linguistic development and word learning through similar mechanisms, such as biologically and experientially through reading, conversation and other experiences that they provide (Hoff-Ginsberg, 1991).

7.3. *Brain electrical activity and WMIC*

There was some support for the increasing specificity of brain function in early childhood hypothesis as there was some increasing specificity of task EEG power between ages 4 and 4½. Specifically, there was increase in baseline-to-WMIC task EEG power for four regions at age 4 (i.e., frontal pole, medial frontal, anterior temporal, and posterior temporal) but an increase for three regions at age 4½ (i.e., frontal pole, medial frontal—left, and posterior temporal). This finding coupled with the previous Wolfe and Bell (2004) result of a baseline-to-WMIC task EEG increase for the medial frontal region at age 4½ lends some support to the increasing specificity hypothesis. The patterns of electrical activation revealed for the 4- and 4½-year-old children in the current study and in our previous work (Wolfe & Bell, 2004) are similar to those found in fMRI work with 7- and 8-year-old children (Casey et al., 1997) and are consistent with the involvement of the prefrontal cortex during WMIC task performance. These are intriguing findings and suggest that the reorganization of the brain, specifically the specialization of function, is occurring during the early childhood years at the same time many higher order cognitive advances are being made. Further, it is promising that these changes may be captured through EEG measures.

An inspection of the ln EEG (6–10 Hz) power values at age $3\frac{1}{2}$ reveals them to be consistently higher than those of the two older age groups. This pattern of activation in which younger children have higher power values in the 6–10 Hz range is characteristic of the developmental pattern of EEG power from infancy to early childhood. Specifically, there is a developmental increase in this frequency band's power from infancy to early childhood, after which time a decrease in power for some scalp regions occurs (Marshall et al., 2002). This pattern of brain activation is perhaps reflective of the spurts in brain growth at 3–10 months and again at 2 and 4 years, the proliferation of neural connections, and then the subsequent reduction of them through the pruning process (Bourgeois, 2001). Also intriguing, baseline and task EEG power at age $3\frac{1}{2}$ did not follow the pattern of activation as seen with the 4- and $4\frac{1}{2}$ -year-old children or even of that seen with infants. One possible explanation for the unique baseline-to-task activation patterns at age $3\frac{1}{2}$ is that the WMIC tasks used in this study may not have been tapping the same WMIC construct in this age group as in the two older groups of children. Perhaps the inclusion of a more age appropriate task for the $3\frac{1}{2}$ -year-old children would have yielded differential patterns of baseline-to-task EEG power. Recall that a good number of the $3\frac{1}{2}$ -year-olds refused the EEG electrodes, so the EEG data gathered here might not be representative of the brain electrical activity of 3-year-olds, in general, performing WMIC tasks. This is likely considering the differences in WMIC task performance and temperament characteristics (i.e., shyness) of those children who chose to participate and those who chose not to participate in the EEG portion of the study. Increasing the number of younger participants with complete behavioral and electrophysiological data might resolve this issue—although if a complete sample of $3\frac{1}{2}$ -year-olds *willing to participate* is selected, then interesting WMIC variability may be lost and temperament-cognition association investigations may be confounded.

We hypothesized that EEG power from the medial frontal region would be associated with individual differences in WMIC task performance. This hypothesis was partially supported. The left and right medial frontal electrode sites were associated with WMIC task performance in the 4-year-old analysis. This association was marginally significant at age $3\frac{1}{2}$ but not significant at age $4\frac{1}{2}$. Even though the marginal results for the $3\frac{1}{2}$ -year-olds were not surprising given the number of children in this data set, the lack of a relation between medial frontal EEG power and WMIC task performance at age $4\frac{1}{2}$ was intriguing. The exploratory regression procedures investigating potential contributions from additional electrode sites yielded perhaps a more accurate picture of brain electrical activity associated with WMIC task performance. This is especially true given the increasing specificity hypothesis implying that multiple brain regions are involved with WMIC processing initially with a focal pattern of association later demonstrated. These findings provide another glimpse of task-related brain electrical activity in early childhood but warrant a replication and further investigation.

7.4. *Limitations*

The generalizability of the findings from this study is bound by some limitations. First, the homogeneity of the participant population is notable and restricts the application of these findings to similar demographic populations only. The large majority of participants were European-Caucasian, have older and well-educated parents, have attended preschool, and have one or two siblings. It is likely that this advantaged sample was not representative of the general population of children with regard to linguistic functioning and perhaps working memory abilities.

Second, the sample size was chosen in consideration of power and the effect sizes of the constructs of interest in the current study. However, due to some children refusing to participate in the WMIC tasks or refusing the application of the EEG equipment, the sample size was reduced. This is especially true for the EEG data and for the 3½-year old age group in particular. Thus, an interpretation of these data must include a caveat regarding those 3½-year-olds who accepted the EEG equipment versus those who refused the equipment. Notably, those 3½-year-olds who accepted the EEG equipment – and contributed data to the current analyses – had higher scores on the WMIC measures than those who refused the equipment and tended to be less shy than their same age peers.

The third limitation of this study is more a statement of caution in the interpretation of the findings rather than a limitation on generalizability. Specifically, it is important to remember that these data are cross-sectional and were collected from three different groups of children. Caution must be used when thinking about the *development of the constructs* and the *development of the associations* between the constructs discussed herein. The best way to address the issue of change and developmental process is to include the same children across the different ages. It is intriguing to consider how these patterns temperament-cognition relations and brain electrical activity might look if the sample was a longitudinal one.

7.5. Conclusion

Working memory, inhibitory control, and cognitive control play a crucial role in a young child's interaction with the environment, and they are important for both cognitive and social domains. Working memory itself is at the seat of many higher-order cognitive, executive, and frontally associated processes including planning, goal setting, and temporal sequencing, and often has a strong linguistic component. As such, it is a process that is uniquely human and the concept of working memory capacity has been associated with the construct of general fluid intelligence (Kane & Engle, 2002). Thus, a consideration of the development of working memory and the associated changes in temperament, linguistic functioning, and brain electrical activity patterns is a valuable research endeavor which could shed light onto perhaps the most important research question of all: What can we do as educators and parents to facilitate the optimal development of these self-regulatory processes?

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