



Published in final edited form as:

Early Educ Dev. 2012 ; 23(1): 59–73. doi:10.1080/10409289.2011.611441.

Early Childhood Predictors of Post-Kindergarten Executive Function: Behavior, Parent-Report, and Psychophysiology

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Abstract

Research Findings—This study examined whether children’s executive functions before kindergarten would predict variance in executive functions after kindergarten. We obtained behavioral (working memory task performance), parental-reported (temperament-based inhibitory control), and psychophysiological (working memory-related changes in heart rate and brain electrical activity) measures of executive functions from a group of preschool-aged children. After children finished kindergarten, approximately 2 years later, parents were asked to complete an assessment of children’s executive function skills. A regression analysis revealed that pre-kindergarten behavioral, parental-reported, and psychophysiological measures accounted for variance in post-kindergarten executive functions. Specifically, working memory task performance, temperament-based inhibitory control, and working memory-related changes in brain electrical activity accounted for unique variance in post-kindergarten executive functions. These data provide a unique contribution to the executive function literature: No other study has examined whether behavioral, psychophysiological, and parental-reported executive function measures can account for unique variance in future executive function.

Practice or Policy—These findings are discussed in relation to children’s transition to school and executive function training programs.

Between 3 and 5 years of age, children exhibit dramatic improvements in executive functions—higher order cognitive and self-regulatory processes, typically associated with the prefrontal cortex, that underlie goal-directed behavior (e.g., Carlson, 2005; Diamond, Prevor, Callender, & Druin, 1997; Wolfe & Bell, 2007a). The fundamental components of executive function include skills such as working memory, inhibitory control, and cognitive flexibility (e.g., Blair, Zelazo, & Greenberg, 2005). Recent research has revealed that preschool- and school-aged children’s executive function skills are related to concurrent and future reading and mathematics performance (Blair & Razza, 2007; Bull, Espy, & Wiebe, 2008; Bull & Scerif, 2001; Clark, Pritchard, & Woodward, 2010; Espy et al., 2004; Mazzocco & Kover, 2007; St. Clair-Thompson & Gathercole, 2006). Likewise, school readiness in preschool-aged children is associated with executive function skills (Bierman, Torres, Domitrovich, Welsh, & Gest, 2009; Blair & Peters, 2003). Deficits in executive function skills, however, have been noted in early-onset disorders such as attention deficit hyperactivity disorder, autism spectrum disorder, and phenylketonuria (PKU) (Diamond et

al., 1997; Semrud-Clikeman, Walkowiak, Wilkinson, & Butcher, 2010). Clearly, understanding the development of executive function skills during early childhood is essential for teachers, parents, and clinicians.

In the present study, we were particularly interested in the relations between pre- and post-kindergarten executive function. Few within-subjects investigations of executive function have included time-points that capture children's transition to school (Hughes, 1998; Hughes, Ensor, Wilson, & Graham, 2010). The kindergarten classroom setting provides a new challenge to children's executive function skills in the presence of numerous distractions. Children are now expected to remain seated for extended periods of time, inhibit off-task behaviors, and exhibit sustained attention when instructed. Measuring executive function after kindergarten provides an estimate of how preschool-aged children's emerging executive function skills are related to an elementary-level of executive function skills found as children transition to formal educational settings. Furthermore, executive function is a multifaceted psychological construct and a combination of behavioral, parental-reported, and psychophysiological measures provides a comprehensive indication of an individual's level of executive function. Few studies (Morasch & Bell, 2011; Wolfe & Bell, 2004, 2007a) have examined the relations among these three types of executive function measures during the preschool period, and none have examined whether different types of executive function measures are equally predictive of future executive function. To this end, we examined whether behavioral, parental-reported, and psychophysiological measures of executive function in preschool-aged children would predict executive function in children after completing kindergarten. In the following sections, we discuss (a) research on behavioral and psychophysiological measures of working memory (and inhibitory control) in preschool-aged children, and (b) parental-reported measures of executive function including temperament-based inhibitory control.

Behavioral Measures of Working Memory

Working memory and inhibitory control are two of the most highly investigated executive function skills during early childhood. Working memory is typically defined as the active maintenance and manipulation of information (Miyake & Shah, 1999), and inhibitory control refers to the suppression of a prepotent response to achieve a goal. In many situations, working memory and inhibitory control are intricately linked (e.g., Davidson, Amso, Anderson, & Diamond, 2006; Roberts & Pennington, 1996). Stroop-like tasks (e.g., day-night, yes-no, mommy-me, grass-snow), which require children to inhibit natural associations, are some of the most widely used working memory/inhibitory control tasks (Carlson, 2005; Diamond et al., 1997; Gerstadt, Hong, & Diamond, 1994; Wolfe & Bell, 2004, 2007a). The general procedure for these tasks is very similar. In the day-night task, for example, children are instructed to say "night" when shown a picture of a sun, and "day" when shown a picture of a moon. Thus, children must maintain the rules of the task in working memory and use inhibitory control to suppress their prepotent response—saying "day" to the sun card and "night" to the moon card—to perform a non-dominant response. As with other executive function tasks, between 3 and 5 years of age, preschool-aged children exhibit variability in working memory/inhibitory control task performance (Carlson, 2005; Diamond et al., 1997; Gerstadt et al., 1994; Wolfe & Bell, 2007a). Preschool-aged children also exhibit variability in performance on tasks that primarily require working memory, such as the forward digit span task (Bull, et al., 2008; Davis & Pratt, 1995; Espy & Bull, 2005). In this task, children must repeat a list of single-digit numbers, typically beginning with a span length of two digits. Therefore, children must maintain information about the digits and the order of digit presentation in working memory (and by default inhibit other information and resist proactive interference from previous trials) for successful task performance. Together, working memory and working memory/

inhibitory control tasks provide information about overlapping, yet different, aspects of executive function during early childhood.

Psychophysiological Measures of Working Memory

The prefrontal cortex is a large area of the brain (approximately 25% of the cerebral cortex) that is located anterior to the premotor cortex and the supplementary motor cortex. The prefrontal cortex is intricately linked to higher order cognitive processes, such as executive functions (Kane & Engle, 2002; Osaka et al., 2003). The structural development of the prefrontal cortex, however, is protracted—proceeding until early adulthood (Huttenlocher, 1979). There is converging biobehavioral evidence that the frontal cortex is a major contributor to working memory/inhibitory control (i.e., A-not-B) task performance during infancy (electroencephalogram (EEG) measure of brain electrical activity: Bell, 2001, 2002, in press; Bell & Fox, 1992, 1997; Cuevas, Bell, Marcovitch, & Calkins, 2010; near-infrared spectroscopy: Baird et al., 2002; PKU: Diamond et al., 1997; lesions with nonhuman primates: Diamond, 1990; Diamond & Goldman-Rakic, 1989). The frontal cortex is also intricately linked to working memory and working memory/inhibitory control task performance during early and middle childhood (EEG: Bell, Wolfe, & Adkins, 2007; Morasch & Bell, 2011; Wolfe & Bell, 2004, 2007a; fMRI: Casey et al., 1995; Thomas et al., 1999; PKU: Diamond et al., 1997).

The EEG is a brain imaging technique that records electrical activity from the scalp, with the assumption that the brain is the origin of these electrical signals (<http://faculty.washington.edu/chudler/1020.html>)¹. EEG offers optimal temporal resolution of brain activity, although the spatial resolution does not match that of functional magnetic resonance imaging (fMRI) used with adults. However, fMRI is extremely sensitive to motor artifacts (i.e., portions of data that cannot be used because of interference from movement), and requires participants to remain relatively motionless in an enclosed area for an extended period of time. These experimental requirements are not ideal for research with young children. Thus, during early childhood, EEG is one of the most preferred brain imaging techniques because of its temporal resolution, noninvasive procedures, and relative resistance to motor artifacts (Casey & de Haan, 2002).

EEG power, a commonly used EEG measure, reflects the summation of the excitability of groups of neurons. Task-related changes in EEG power from a resting baseline are considered indicative of cognitive processing during working memory tasks. The same pattern of task-related changes in EEG power has been noted during infancy and early childhood: Task-related EEG changes are exhibited by children with high, but not low, working memory/inhibitory control performance (Bell, 2001; Wolfe & Bell, 2007a). Although working memory/inhibitory control-related EEG activity was widespread (i.e., all scalp locations) during infancy, working memory/inhibitory control-related EEG activity was limited to the scalp locations overlying medial frontal cortex (hypothesized to reflect prefrontal activation) during early childhood (Bell & Wolfe, 2007).

Cardiac measures, such as heart rate (HR), also provide researchers with a noninvasive method for examining physiological responses associated with cognitive processing (see Reynolds & Richards, 2008, for a review). The electrical activity of the heart is measured by placing electrodes (sensors) at specific locations on the body (e.g., chest, both arms, arm and leg, back). Research on working memory and working memory/inhibitory control tasks has

¹The “Neuroscience for Kids” website is supported by government funding and consistently maintained and updated by a neuroscientist. This website is intended to be a resource for anyone interested in learning about the nervous system. We believe this website will be particularly useful for early educators who want to incorporate neuroscience into their classroom activities.

revealed task-related changes in HR for infants, children, and adults (Bell, in press; Hansen, Johnsen, & Thayer, 2003; Van Leijenhorst, Crone, & Van der Molen, 2007; Wolfe & Bell, 2004). HR is directly affected by activation of the parasympathetic and sympathetic nervous systems. The brain evokes changes in HR via the parasympathetic and sympathetic nervous systems, and it is plausible that cardiac activity and prefrontal cortical activity are linked.

Parental-Reported Measures of Executive Function

In children's daily routines, they encounter a variety of circumstances that require the use of executive function skills. For instance, when engaged in social pretend play, children must use working memory to remember their role and their playmates' roles, inhibitory control to inhibit acting out of character, and cognitive flexibility to adapt to changes in the shared plot (Diamond, 2010). It is nearly impossible for a single laboratory visit to capture the range of executive function skills that children utilize on a daily basis. Parents, on the other hand, are witness to a wide range of situations in which children might exhibit executive function skills. Thus, parental-report may capture ecologically valid and important aspects of children's developing executive function skills that are not assessed in laboratory-based tasks.

The Child Behavior Questionnaire (CBQ) is a parental-report assessment of children's temperament (Rothbart, Ahadi, Hershey, & Fischer, 2001). Temperament is typically defined as biologically-based individual differences in emotional reactivity and self-regulation (Rothbart & Bates, 2006). Temperament-based inhibitory control refers to the ability to modify inappropriate behaviors under instruction or in novel situations (Rothbart et al., 2001). During early childhood, executive function skills and the temperament-based inhibitory control are related: Higher levels of inhibitory control are associated with higher levels of executive function (Carlson & Moses, 2001; Kochanska, Murray, & Coy, 1997; Morasch & Bell, 2011; Wolfe & Bell, 2004, 2007a). Although some subscales of the CBQ measure aspects of executive function, the CBQ was not explicitly designed as an assessment of executive function.

The Behavior Rating Inventory of Executive Function (Preschool Version; BRIEF-P) is a parental-report assessment developed to measure children's executive function (Gioia, Espy, & Isquith, 2003). It includes subscales for various executive function skills (e.g., Working Memory, Inhibit, Shift) which sum to comprise an overall measure of executive function—the Global Executive Composite (GEC). Although the BRIEF-P was designed to accompany clinical assessments of dysfunctions in executive function, it also provides researchers with a measure of children's executive function skills as exhibited in a range of situations that they encounter on a daily basis. There is evidence that during early childhood, BRIEF-P scores for typically developing children are related to performance on laboratory-based executive function tasks (e.g., Clark et al., 2010).

Hypotheses

We hypothesized that behavioral (working memory performance), parental-reported (temperament-based inhibitory control), and psychophysiological (working memory-related EEG and HR) measures of executive function during the preschool period would predict children's executive function (GEC on BRIEF-P) after completing kindergarten. Furthermore, we hypothesized that higher levels of working memory performance and inhibitory control in preschool-aged children would predict higher levels of post-kindergarten executive function.

Method

Participants

A total of 64 preschool-aged children (29 girls, 35 boys; 5 Hispanic, 59 Non-Hispanic; 55 Caucasian, 1 African American, 7 Multi-Racial, 1 Other) and their mothers were participants in a longitudinal study examining the early development of executive function from infancy through early childhood. Children were seen between 4 years 0 weeks and 4 years 21 weeks of age ($M = 4$ years 6 weeks, $SD = 4$ weeks) for their laboratory visit so that only 4.8 months separated the youngest and oldest children. Mothers completed the BRIEF-P the summer after children finished kindergarten when they were between 5 years 36 weeks and 6 years 45 weeks ($M = 6$ years 16 weeks, $SD = 18$ weeks). All children were born within 2 weeks of their expected due dates and had no diagnosed neurological problems or developmental delays. All parents completed a high school education, and 71% also had a college degree. Average maternal and paternal age at birth was 30.0 and 33.6 years ($SD = 4.5$ and 6.1), respectively. Children were given a small gift during their laboratory visit and mothers were paid for completing the BRIEF-P.

General Procedure

Prior to visiting the research laboratory, mothers were mailed the CBQ and were asked to complete it at home. On arrival to the laboratory, the experimenter greeted each child and parental consent and child verbal assent were obtained. The experimenter engaged the child with age-appropriate toys to help the child acclimate to the research laboratory and build rapport with the experimenter. After this period, the application of EEG and ECG electrodes occurred. While continuous EEG and ECG were recorded, children completed a baseline phase and then working memory tasks were administered. After children finished kindergarten, mothers were mailed the BRIEF-P and were asked to complete it and mail it back to the laboratory. Each of the aforementioned assessments is described in more detail below.

Working Memory Tasks

Two tasks were used to investigate children's working memory: the forward digit span task and the mommy-me task. Each task required the preschool-aged children to maintain information in an active state and update memory representations of that information from trial to trial.

The forward digit span task primarily requires working memory (Espy & Bull, 2005), but there is also the potential of proactive interference from previous trials. The experimenter asked the child to repeat a list of single-digit numbers beginning with a span length of two digits (Espy & Bull, 2005). Children were given two learning trials and six test trials: two 2-, 3-, and 4-digit span trials. The total administration time was approximately 2 min. The proportion of correct test trials was calculated.

The mommy-me task required the child to remember two rules and exhibit inhibitory control by performing a subdominant response. The mommy-me task was created in our lab and is conceptually and procedurally similar to other Stroop-like tasks, such as the day-night, yes-no, and grass-snow tasks (Carlson, 2005; Diamond et al., 1997; Gerstadt et al., 1994; Wolfe & Bell, 2004, 2007a). At the beginning of the appointment, the experimenter took individual pictures of each child and her mother. During the mommy-me task, the child was instructed to say "mommy" when shown a picture of herself and to say "me" when shown a picture of her mother. The child was given two learning trials and 10 test trials: five with the mom picture and five with the child picture arranged in a pseudorandom order. Again, the total

administration time was approximately 2 min, and the proportion of correct test trials was calculated.

Each visit was videotaped for later coding. Trained observers coded each of the working memory tasks, with a second observer reliability coding 22-25% of the sample. The percentage of agreement between the two coders for the children's performance on the forward digit span and mommy-me tasks was 99% and 91%, respectively. Disagreements in coding were discussed, with the final determination of the scores made by the third author. The variable of interest was the average percentage of correct trials across both working memory tasks (WM2 proportion).

EEG and ECG were recorded continuously during both working memory tasks. WM2 EEG power and HR values were calculated by averaging the EEG power values and HR values from the forward digit span and mommy-me tasks, with the final physiological variables weighted by the amount of artifact-free data available for each task. To retain as much data as possible, if children were missing behavioral, EEG, or ECG data from a single working memory task, then WM2 represented only available data from the other working memory task.

Maternal Report Measures

Temperament-based inhibitory control: Pre-kindergarten—The CBQ was administered to establish a temperament-based report of child inhibitory control. Although all CBQ temperament subscales were collected, the inhibitory control subscale was of particular interest in the current study. This 13-item scale had high internal consistency ($\alpha = .74$; Rothbart et al., 2001). Mothers rate their agreement with how accurately each item described their children's behavior (1 = *extremely untrue*, 7 = *extremely true*) during the 2 weeks prior to the laboratory visit. For instance, "My child approaches places s/he has been told are dangerous slowly and cautiously." The questionnaire was mailed to mothers in advance and was collected on their arrival at the laboratory.

Global executive composite: Post-kindergarten—Following children's completion of kindergarten, their mothers were mailed the BRIEF-P. The BRIEF-P was administered to establish a rating of children's daily executive function in a variety of contexts. This 63-item scale had high internal consistency ($\alpha = .95$; Gioia et al., 2003). Mothers rate how often their children exhibit various behaviors (1 = *never*, 2 = *sometimes*, 3 = *often*) during the past 6 months. For instance, "acts too wild or out of control" (Inhibit); "resists change of routine, foods, places, etc." (Shift); "overreacts to small problems" (Emotional Control); "when given two things to do, remembers only the first or last" (Working Memory); "when instructed to clean up, puts things away in a disorganized, random way" (Plan/Organize). All scales (i.e., Inhibit, Working Memory, Shift, Emotional Control, Plan/Organize) are summed to create the GEC score (Gioia et al., 2003). The BRIEF-P is reverse scaled; lower GEC scores represent higher levels of executive function.

Physiological Measures

EEG recording—EEG is a psychophysiological tool used to record and measure electrical activity from the scalp that is related to underlying cortical activity (Stern, Ray, & Quigley, 2001). Continuous EEG recordings were collected throughout a battery of tasks in an ongoing longitudinal examination of executive function development. Recordings made during the digit span and mommy-me tasks are described and reported in the current study.

EEG was recorded during a baseline and during the working memory tasks so that the EEG in a quiet state could be compared with the EEG during effortful cognitive processing.

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. EEG was recorded using a stretch cap (Electro-Cap, Inc.) with electrodes in the 10/20 system pattern (Jasper, 1958). Following the recommended protocol (Pivik et al., 1993), EEG gels were dispensed into each recording site from a 5-ml plastic syringe equipped with a blunt tip. To prepare the scalp for the EEG recording, a small amount of abrasive (NuPrep) gel was placed into each recording site, and the scalp was gently rubbed with the smooth wooden end of a cotton swab. Following this, conductive gel provided by the cap manufacturer was placed in each site. Electrode impedances were measured and accepted if they were below 10K ohms. The electrical activity from each lead was amplified using separate SA Instrumentation Bioamps (San Diego, CA) and bandpassed from 0.1 to 100 Hz. Activity for each lead was displayed on the monitor of an acquisition computer. The EEG signal was digitized on-line at 512 samples/s for each channel so that the data were not affected by aliasing. The acquisition software was Snapshot-Snapstream (HEM Data Corp.; Southfield, MI) and the raw data were stored for later analyses.

The 6- to 9-Hz frequency band was selected for analysis because young children show a dominant peak in EEG rhythms within this frequency range from infancy (Bell & Fox, 1994) into childhood (Marshall, Bar-Haim, & Fox, 2002). In previous biobehavioral investigations of cognitive development, the 6- to 9-Hz band was shown to discriminate successful and unsuccessful overall cognitive performance (Bell, 2001, in press; Wolfe & Bell, 2004) on working memory tasks for infants and preschool-aged children. EEG activity within this band also revealed performance-related differences in sustained attention task in a cross-sectional study of 8- to 11-month-olds (Orekhova, Stroganova, & Posikera, 1999). During infancy and early childhood, the 6- to 9-Hz frequency band shares some qualities with the bands of adult alpha and adult theta, which have been associated with cognitive processing during adult short-term memory tasks (Klimesch, Schimke, & Schwaiger, 1994). Therefore, the selected frequency band was both age-appropriate and the most likely to reveal individual differences on childhood working memory tasks.

EEG analysis—EEG data were examined and analyzed using EEG Analysis System software developed by James Long Company (Caroga Lake, NY). First, the data were re-referenced via software to an average reference configuration. The re-referenced EEG data were artifact scored for eye movements and gross motor movements and these artifact-scored epochs were eliminated from all subsequent analyses. The data then were analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1-s width and 50% overlap. Power was computed for the 6-9 Hz frequency band. The power was expressed as mean square microvolts and the data were transformed using the natural log (ln) to normalize the distribution.

ECG recording and analysis—ECG also was measured during baseline and task from two disposable electrodes using modified lead II (right collarbone and lower left rib; Stern et al., 2001), grounded at the scalp near electrode site Fz. The cardiac electrical activity was amplified using a SA Instrumentation Bioamp and the QRS complex was displayed on the acquisition computer monitor along with the EEG data. The cardiac signal was digitized at 512 samples per second. The acquisition software was Snapshot-Snapstream (HEM Data Corp.) and the raw data were stored for later analyses.

Heart data were examined and analyzed using IBI Analysis System software developed by James Long Company. First, R waves were detected and movement artifact, designated by the absence of at least three consecutive R waves, was scored. These artifact-scored epochs were eliminated from all cardiac calculations. HR was calculated as beats per minute.

Baseline—Baseline EEG and ECG were recorded for 1 min while the child watched a neutral cartoon that provided a period of physiology (psychophysiological data) containing comparable eye movements and gross motor artifact to what is typically exhibited during the working memory tasks. Mothers were instructed not to talk to their child during the EEG/ECG recording. Immediately after baseline, the recording of EEG and ECG continued as the working memory tasks were administered.

Results

In our examination of the relation between pre- and post-kindergarten executive function, we first report mean performance on the working memory tasks, temperament-based inhibitory control, and children's GEC score on the BRIEF-P. This is followed by two sets of correlation analyses: (a) between working memory tasks and (b) among behavioral, maternal-reported, and psychophysiological variables. Finally, multiple regression was used to examine the relations between pre-kindergarten behavioral, psychophysiological, and parental-reported executive function and post-kindergarten executive function as measured by the GEC on the BRIEF-P.

Forty-nine mothers completed and returned the BRIEF-P. Independent groups *t*-tests were conducted for all measures of interest and revealed no difference in children with or without BRIEF-P scores (all *t*'s ≤ 1.56 , all *p*'s $> .10$). Because our hypotheses focused on predicting variance in post-kindergarten executive function, we only report data for children who have both pre- and post-kindergarten executive function measures.

Mean scores of each executive function measure are displayed in Table 1. Of the 49 children with BRIEF-P measures, three were missing mommy-me behavioral data because they refused to participate and 11 were missing forward digit span behavioral data due to experimenter error, video malfunction, child fussiness, and failure to pass the learning trials. In addition, one child was missing CBQ data because the questionnaire was not returned. Independent groups *t*-tests were conducted for all measures of interest and revealed no differences between children with and without missing preschool executive function data (all *t*'s ≤ 1.32 , all *p*'s $> .10$).

Table 1 reveals that preschool children exhibited a wide range of individual differences in performance on each working memory task. A Pearson correlation was calculated between the mommy-me and forward digit span tasks. There was a marginally significant positive correlation between the two working memory measures, $r(38) = 0.31$, $p = .06$. Thus, due to the statistical and conceptual relations between the two working memory measures, the composite score (WM2) was used in all remaining analyses.

Due to some children refusing the EEG and/or ECG equipment, the sample size was further reduced. Four children refused the application of gels, application of HR electrodes, or to wear the EEG electrode cap for the entire protocol. Motor artifacts in EEG and/or ECG data resulted in no usable data for five additional children. Independent groups *t*-tests were conducted for all measures of interest and revealed no differences between children who did and did not refuse the physiological equipment (all *t*'s ≤ 1.65 , all *p*'s $> .10$). However, children with no psychophysiological data because of motor artifacts had lower post-kindergarten GEC scores than children who had usable data ($M = 79.40$ and 95.81 , $SD = 15.04$ and 17.28 , respectively), $t(40) = 2.02$, $p = .05$. (Lower GEC scores are representative of higher levels of executive function skills.) These children did not differ on any other variable of interest (all *t*'s < 1.00 , all *p*'s $> .10$). For subsequent analyses, baseline-to-task change (i.e., task minus baseline) scores were computed for psychophysiological data.

Thirty-seven children had sufficient pre- and post-kindergarten executive function data for subsequent analyses. Correlations among pre-kindergarten executive function measures (behavioral, psychophysiological, parental-report) and post-kindergarten executive function are displayed in Table 2. The results from a multiple regression analysis are displayed in Table 3. Together, pre-kindergarten measures of working memory (behavioral, EEG, HR) and temperament-based inhibitory control accounted for 57% of the variance in post-kindergarten GEC on the BRIEF-P. An examination of the regression weights revealed that WM2 task performance, WM2 task-related changes in EEG power at medial frontal scalp locations, and temperament-based inhibitory control accounted for unique variance in post-kindergarten GEC (Table 3).

Discussion

During early childhood, the transition to school is a significant event that is associated with new challenges for children's executive function skills. Yet, few within-subjects investigations have assessed executive function skills before and after entering kindergarten (Hughes, 1998; Hughes et al., 2010). In the present study, we used a longitudinal design to examine if behavioral (working memory task performance), psychophysiological (working memory-related changes in HR and EEG power), and parental-reported (temperament-based inhibitory control) executive function measures obtained prior to kindergarten would predict parental-reported GEC (on BRIEF-P) after kindergarten. Analyses yielded valuable information regarding the relation between executive function measures before and after the transition to school. Furthermore, the data provide a unique contribution to the executive function literature: No other study has examined whether behavioral, psychophysiological, and parental-reported executive function measures can account for unique variance in future executive function.

Pre-kindergarten executive function measures accounted for 57% of the variance in post-kindergarten executive function. This finding is particularly impressive considering that approximately 2 years elapsed between assessments. During this 2-yr span, children exhibit substantial improvements in executive function skills, which are presumably related to the maturation of frontal areas (e.g., Davidson et al., 2006; Diamond et al., 1997; Gerstadt et al., 1994). Thus, despite these behavioral and physiological changes, it appears that individual differences in executive function measures before and after kindergarten are strongly related. Specifically, we found that pre-kindergarten measures of temperament-based inhibitory control, working memory task performance, and working memory-related changes in EEG power at medial frontal scalp locations were unique predictors of post-kindergarten executive function. The majority of this variance was captured by parental-reported (temperament-based inhibitory control) and behavioral (working memory task performance) measures—the two types of executive function measures most frequently obtained during early childhood (e.g., Carlson, 2005; Clark et al., 2010). As hypothesized, higher post-kindergarten executive function skills (i.e., lower GEC scores) were associated with higher pre-kindergarten levels of temperament-based inhibitory control and higher pre-kindergarten working memory task performance. Accordingly, our findings support the validity of using behavioral and parental-reported measures when predicting future executive function during early childhood.

Although the majority of variance in post-kindergarten executive function was accounted for by behavioral and parental-reported measures, changes in EEG power at medial frontal scalp locations during working memory tasks accounted for a unique proportion of the residual variance. Thus, psychophysiological measures of executive function provide researchers with additional information about children's executive function that is not captured by other types of measures. Furthermore, this finding gives further evidence of the role of the frontal

brain electrical activity in executive function skills during early and middle childhood (Bell et al., 2007; Casey et al., 1995; Diamond et al., 1997; Morasch & Bell, 2011; Thomas et al., 1999; Wolfe & Bell, 2004, 2007a). Working memory-related changes in HR, however, did not account for unique variance in post-kindergarten executive function. Previous studies have found that working memory/inhibitory control-related changes in HR accounted for significant variance in concurrent working memory/inhibitory control performance during infancy (Bell, in press; Cuevas et al., 2010). It appears that, during early childhood, other types of executive function variables might be better predictors of future executive function than HR. It is plausible, however, that other cardiac measures, such as heart rate variability, may exhibit a stronger association with future executive functioning. Thus, although cardiac measures, such as HR, are potentially related to executive function skills during early childhood, additional research is necessary to further understand this association.

Our findings are consistent with previous research that has examined the concurrent relations among behavioral, maternal-reported, and psychophysiological executive function measures during early childhood. For toddlers, working memory task performance and working memory-related changes in EEG power at frontal scalp locations were unique predictors of temperament-based inhibitory control (Morasch & Bell, 2011). Likewise, between 3.5 and 4.5 years, parental-reported temperament—effortful control (i.e., a temperament composite that includes the inhibitory control subscale) and approach—and working memory-related changes in frontal EEG power were predictors of concurrent working memory task performance (Wolfe & Bell, 2004, 2007a, 2007b). Together, the findings of the aforementioned studies and our findings confirm that different types of executive function measures provide overlapping, yet unique, information about an individual's executive function skills.

There is increasing evidence that preschool executive function training programs are effective at improving children's executive function skills (Diamond, Barnett, Thomas, & Munro, 2007; Thorell, Linqvist, Nutley, Bohlin, & Klinberg, 2009). For instance, Thorell et al. (2009) found that after a 5-week working memory training program, preschool-aged children exhibited significant improvements on trained and non-trained spatial and verbal working memory tasks as compared to children in a control group. However, these studies have not examined the stability of executive function training effects after children's transition to school. In the present study, pre-kindergarten measures of executive function were predictive of post-kindergarten executive function. Accordingly, we hypothesize that the effects of executive function training programs will persist after children's transition to school. Clearly, additional research on the long-term effects of executive function training programs is essential for our understanding of executive function in early education.

Previous research has found that BRIEF-P (Gioia et al., 2003) scores are related to concurrent performance on laboratory-based executive function tasks (e.g., Clark et al., 2010). Our data also support the external validity of the BRIEF-P; GEC scores were associated with multiple types of executive function measures (behavioral, psychophysiological, parental-reported) obtained prior to kindergarten. The BRIEF-P, however, was our only measure of post-kindergarten executive function. It is plausible that behavioral, psychophysiological, and maternal-reported measures of pre-kindergarten executive function would account for different percentages of unique variance in post-kindergarten executive function if a different type of executive function measure was examined (i.e., behavioral or psychophysiological). Ideally, future research would use a variety of behavioral, psychophysiological, and parental-reported executive function measures at both time points to provide a comprehensive understanding of changes in children's executive function skills. Furthermore, it is plausible that kindergarten is used as a transition period for children entering formalized education, and that there are substantial

increases in teacher's demands of executive function skills once children enter the 1st grade. Whether the strong predictive relation between preschool and future executive function would be found if post-1st grade executive functions were examined is a question for future empirical investigations.

The generalizability of our findings is potentially limited by the homogeneity of our participant population. The majority of participants had older, college-educated parents, which is not representative of the general population of children. To this end, we are currently collecting pre- and post-kindergarten executive function data from a diverse sample that is more representative of the general population.

The transition to school is associated with new challenges for children's executive function skills. Our longitudinal assessment provides initial evidence that behavioral, psychophysiological, and parental-reported executive function measures obtained prior to kindergarten are predictive of children's post-kindergarten executive function skills. These findings support the notion that executive function is a multifaceted construct in which individual differences are best characterized by using a variety of executive function measures.

Acknowledgments

This research was supported by grants HD049878 and HD043057 from the *Eunice Kennedy Shriver* National Institute of Child Health and Human Development (NICHD) awarded to Martha Ann Bell. The content of this manuscript is solely the responsibility of the authors and does not necessarily represent the official views of the NICHD or the National Institutes of Health. We are grateful to the families for their participation in our research and to our research team for their assistance with data collection and coding. The assistance of Lisa Buonomano, Anjolie Diaz, and Vinaya Raj is gratefully acknowledged.

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Table 1
Descriptive Statistics for Pre- and Post-Kindergarten Measures of Executive Function

Measure	<i>M</i>	<i>SD</i>	Min	Max	<i>n</i>
<i>Pre-Kindergarten Measures</i>					
MM proportion correct	0.83	0.20	0.20	1.00	46
FD proportion correct	0.83	0.19	0.33	1.00	38
WM2 proportion correct	0.83	0.17	0.35	1.00	46
Temperament-based IC	4.62	0.61	3.00	5.55	48
<i>Post-Kindergarten Measure</i>					
BRIEF-P: GEC	93.12	17.11	64.00	143.00	49

Note: MM = momny-me; FD = forward digit; WM2 = working memory composite; IC = inhibitory control; GEC = global executive composite

Table 2
Correlations Among Pre- and Post-Kindergarten Measures of Executive Function

	GEC	WM2 prop	WM2 EEG	WM2 HR
<i>Post-Kindergarten Measure</i>				
BRIEF-P: GEC	-			
<i>Pre-Kindergarten Measures</i>				
WM2 proportion correct	-.59***	-		
WM2 task-related change: medial frontal EEG power	.17	.01	-	
WM2 task-related change: HR	.03	.05	-.20	-
Temperament-based IC	-.40**	-.02	.14	-.17

Note: GEC = global executive composite; WM2 = working memory composite; HR = heart rate; IC = inhibitory control;

$n = 37$.

 $p < .001$

**
 $p < .01$.

Table 3
Results of Multiple Regression Analysis Predicting Post-Kindergarten Executive Function from Pre-Kindergarten Behavioral, Parental-Report, and Psychophysiological Executive Function Measures

	<i>R</i>	<i>R</i> ²	<i>F</i>	<i>B</i>	<i>t</i>	<i>sr</i> ²
<i>Dependent variable: Post-kindergarten GEC (BRIEF-P)</i>						
WM2 proportion correct	.76	.57	10.79	-.60	-5.21	*** .36
WM2 task-related change: medial frontal EEG power				.24	2.04	* .05
WM2 task-related change: HR				.03	0.28	
Temperament-based IC				-.44	-3.72	*** .18

Note: GEC = global executive composite; WM2 = working memory composite; HR = heart rate; IC = inhibitory control;

Only *sr*² values .01 are reported. *n* = 37.

p < .001

*
p < .05.