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The Role of Inhibitory Control in Behavioral and Physiological Expressions of Toddler Executive Function

Katherine C. Morasch and Martha Ann Bell

Virginia Polytechnic Institute and State University

Abstract

Eighty-one toddlers (ranging from 24 to 27 months) participated in a biobehavioral investigation of inhibitory control. Maternal-report measures of inhibitory control were related to laboratory tasks assessing inhibitory abilities under conditions of conflict, delay, and compliance challenge as well as toddler verbal ability. Additionally, unique variance in inhibitory control was explained by task-related changes in brain electrical activity at lateral frontal scalp sites as well as concurrent inhibitory task performance. Implications regarding neural correlates of executive function in early development and a central, organizing role of inhibitory processing in toddlerhood are discussed.

One of the most intriguing issues in contemporary developmental cognitive neuroscience focuses on the development of executive functions (EF) and the neurological systems that support these abilities. EF is a psychological construct that refers to higher-order cognitive and self-regulatory processes coordinating thought and action (Carlson, 2005). These processes include working memory, inhibitory control, cognitive flexibility, planning, and behavioral organization associated with goal-directed action (Blair, Zelazo, & Greenberg, 2005; Eslinger, 1996; Zelazo, Carter, Reznick, & Frye, 1997). Individual differences in EF have been associated with developmental improvements in socialization (Hughes, Dunn, & White, 1998), conscience (Kochanska, Murray, & Coy, 1997), and school readiness (Blair, 2002; Blair, Granger, & Razza, 2005; Diamond, Barnett, Thomas, & Munroe, 2007).

Inhibitory control is a central component of EF and generally focuses on the ability to actively inhibit or delay a dominant response to achieve a goal. Inhibitory abilities have been examined multiple ways in the laboratory, usually under conditions of conflict, delay, or other challenges (Carlson & Moses, 2001). Inhibitory control begins to emerge towards the end of the first postnatal year and undergoes rapid development across the toddler period and into the preschool years, a pattern coinciding with age-related changes in frontal lobe maturation and connectivity (Diamond, 2002; Diamond et al., 2007; Diamond, Prevor, Callendar, & Druin, 1997; Luria, 1973; Wolfe & Bell, 2007). Individual differences in the expression of inhibitory control may play a significant role in toddlers' adaptive functioning, as children transitioning from infancy are now expected by parents to be able to regulate their behavior in accordance with external demands reflecting day-to-day challenges of conflict, delay, and compliance in typical situations (e.g., stopping enjoyable activities, waiting for meals, cleaning up toys; Kochanska et al., 1997; Kopp, 1982, 2002).

Corresponding Author: Katherine C. Morasch, Ph.D., Department of Psychology, 311 Williams Hall (0436), Virginia Tech, Blacksburg, VA 24061, kacolo@vt.edu, Phone: (540) 231-1116, Fax: (540) 231-3652.

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Much of the research on day-to-day challenges, with respect to inhibitory control, can be found in the temperament literature. Rothbart's definition of temperament-based inhibitory control shares many characteristics with an EF-based definition of inhibitory control. For example, on the parent-report Early Childhood Behavior Questionnaire (ECBQ), the inhibitory control subscale is comprised of items that describe a toddler's capacity to stop, moderate, or refrain from a behavior under instruction (Putnam, Garstein, & Rothbart, 2006). These items reflect parents' perceptions of how toddlers meet the day-to-day demands of conflict, delay, and compliance challenges. Much like EF-based inhibitory control, temperament-based inhibitory control is dependent upon executive attention processes associated with frontal lobe development (Posner & Rothbart, 2000, 2007).

Therefore, a multi-faceted exploration that encompasses behavioral, parent-report, and physiological measures of inhibitory control during toddlerhood is likely to reveal a wide range of individual differences in this executive ability. Of the few existing investigations linking brain-based mechanisms and inhibitory control in early development (for a review see Bell & Morasch, 2007), we know of no data that directly measure ongoing neurological activity associated with inhibitory control expression in the toddler period. The purpose of our study was to investigate the comprehensive role of inhibitory control during the toddler period by first examining relations among laboratory-based and temperament-based expressions of inhibitory control, and then by describing patterns of brain-based physiological change associated with individual differences in inhibitory control abilities.

Measurement of Inhibitory Control in Early Development

Significant changes in inhibitory processes are clearly identifiable from infancy through early childhood. As is the case with EF in general, there is currently no universal agreement on a single unifying measure of inhibitory control, and there are multiple approaches to the study of this ability (Blair et al., 2005; Carlson, 2005; Carlson & Moses, 2001). These approaches include observed behavioral expressions of inhibitory control on laboratory-based tasks, as well as parent-report measures of inhibitory control. These laboratory-based and parent-report measures are associated in early development (Carlson & Moses, 2001; Kochanska et al., 1997; Kochanska, Murray, & Harlan, 2000).

Laboratory-based measures of inhibitory control

In a recent review of EF tasks appropriate for use in developmental populations, Carlson (2005) described a battery of age-appropriate measures for examining EF in toddlers and preschoolers. Studies exploring inhibitory control in early development highlight three general categories of laboratory-based inhibitory control tasks: those that require young children to inhibit activity under conditions of conflict, delay, and compliance (Carlson & Moses, 2001; Diamond et al., 1997-, 2007; Gerstadt, Hong, & Diamond, 1994; Kochanska et al., 2000, Stifter, Spinrad, & Braungart-Rieker, 1999).

Conflict-based assessments of inhibitory control refer to measures that require children to learn a set of rules and to inhibit a dominant response (e.g., saying "day" when shown a drawing of the sun; tapping twice when the experimenter taps twice) when faced with a salient conflict in order to produce a non-dominant response (e.g., saying "day" when shown a drawing of a moon; tapping twice when the experimenter taps once; Carlson & Moses, 2001; Diamond et al., 1997). Preschool children's performance on conflict tasks has been associated with frontal brain-electrical activity measured via the electroencephalogram (EEG; Wolfe & Bell, 2004, 2007).

Although documented for appropriate use with toddler populations, many of the tasks described in Carlson's battery (2005) have components that require toddlers to respond

motorically. This creates additional challenges for inclusion within a biobehavioral protocol, specifically one that includes measures of brain-electrical activity. To represent conflict conditions in a toddler inhibitory control assessment compatible with EEG recording, we developed a looking version of the A-not-B task with invisible displacement. In this version of the task, response requirements were changed from manual search to visual search for the location of a hidden item following a standard delay. We have previously developed a looking version of the classic infant A-not-B task for the purpose of collecting EEG during task performance (Bell, 2001, 2002; Bell & Adams, 1999). Similar to the classic infant A-not-B task, success on the A-not-B task with invisible displacement requires the toddler to be able to remember where a reward is hidden and to inhibit responding based on the location of previous rewards (i.e., conflicting conditions; Diamond et al., 1997). Performance on the reaching version of the infant A-not-B task has been empirically shown to require the function of the dorsolateral prefrontal cortex (Baird, Kagan, Gaudette, Walz, Hershlag, & Boas, 2002; Diamond, 1990; 1991). Similarly, infants who demonstrate better performance on our looking version of the infant A-not-B task show task-related changes in EEG power at frontal and other scalp locations during task performance (Bell, 2001).

Delay-based assessments of inhibitory control include tasks requiring children to withhold or suppress a dominant response in the face of a salient (often attractive) activity (e.g., Calkins, 1997; Kochanska et al., 2000; Vaughn, Kopp, & Krakow, 1984). For example, the experimenter shows a young child an attractive toy (i.e., a new box of crayons) but does not allow the child to play with it. After placing the toy within the child's reach, the child is explicitly told not to touch the toy. The experimenter then leaves the room for a period of time before returning and granting permission for the child to play with the toy. Thus, the child must delay play (i.e., suppressing a dominant response) with a desirable object in the face of a salient activity.

Compliance-based assessments offer an opportunity to examine inhibitory control under the challenging conditions associated with research procedures (Kochanska et al., 1997; Vaughn et al., 1984). Laboratory tasks requiring young children to engage in typical but mundane activities (e.g., cleaning up toys) have been associated with parent-reported inhibitory control. Compliant children had higher ratings of parent-reported inhibitory control than children who refused to clean up the toys (Kochanska et al., 1997). In addition, Stifter and colleagues examined heart rate electrode placement and compliance in toddlerhood and found that rejection of physiological electrodes (heart rate stickers) was associated with maternal report of toddler inhibitory control (Stifter et al., 1999). Children who complied with the experimenter and allowed the electrodes to be placed for physiological recordings were rated by their parents as having higher inhibitory control abilities than toddlers who did not allow electrode placement.

Temperament-based measures of inhibitory control

Rothbart defines temperament as biologically-based individual differences in reactivity and self-regulation (Rothbart, 1989; Rothbart & Bates, 2006). According to Rothbart, temperament-based inhibitory control is a unique form of self-regulation that emerges at the end of the first year of life and is closely related to the development of attention networks (Posner & Rothbart, 2000). Inhibitory control in this framework refers to the conscious modification of behavior, including starting or continuing undesirable activities and stopping or avoiding pleasurable activities (Rothbart, 1989).

Temperament-based inhibitory control in toddlers is often measured using the ECBQ (Putnam et al., 2006). Designed for use with 18- to 36-month-olds, the ECBQ is comprised of individual items assessing general patterns of toddler reactivity and regulation in and across everyday contexts. From these items, 18 subscales and 3 broad factors of

temperament are derived. The inhibitory control subscale describes a toddler's capacity to stop, moderate, or refrain from a behavior under instruction (Putnam et al., 2006) and includes items such as, "When asked not to, how often did your child touch an attractive item (such as an ornament) anyway?". Parents' ratings of temperament-based inhibitory control have previously been related to laboratory-based tasks of inhibitory control behaviors in young children (Carlson & Moses, 2001; Kochanska et al., 1997). Parent-rated measures of inhibitory abilities may be especially informative for use in examining toddler inhibitory control. Parents contribute valuable information about their toddler's abilities to inhibit behavior under demands of conflict, delay, and compliance in a wide variety of naturalistic settings that may not be fully captured within the constraints of a laboratory protocol.

Contributions of verbal ability to inhibitory control

Previous research has demonstrated a strong association between executive abilities, including inhibitory control, and verbal abilities (e.g., Kaler & Kopp, 1990) in early development. Additionally, Hughes (1998) demonstrated that verbal ability was related to the expression of inhibitory control in a sample of preschool children and Carlson and Moses (2001) found that verbal ability was related to performance on both conflict- and delay-based tasks of inhibitory control. Given the degree of individual differences in both verbal ability and inhibitory control at age two, we examined contributions from language development to relations among inhibitory measures.

Hypothesis

We hypothesized that performance on laboratory-based assessments of inhibitory control would have significant associations with maternal-report of inhibitory control processes in toddlerhood, including dimensions of inhibitory control under conditions of conflict, delay, and compliance. Due to the documented relation between inhibitory control and verbal abilities (e.g., Kaler & Kopp, 1990), we expected that contributions from language would also account for variance in maternal-report of inhibitory ability.

Neural Correlates of Inhibitory Control Development

Evidence from atypical and healthy populations has consistently highlighted the integrity and function of the frontal lobe as the neurological substrate for EF development and function (Diamond et al., 1997). The development of the frontal lobe is unique from other cortical areas in that it is both delayed (typically not functionally mature until the second half of the first year of life as indicated by associations with task performance; Bell & Fox, 1994; Chugani, 1994; Diamond, 2001, 2002; Goldman-Rakic & Leung, 2002), and protracted (it continues to structurally develop from infancy and into early adulthood; Luna, Carver, Urban, Lazar, & Sweeney, 2004). Anatomical, neuropsychological, and biobehavioral work with developmental populations have all implicated the unique development and function of the frontal cortex in supporting individual and age-related differences in inhibitory mechanisms (Bell & Morasch, 2007; Bell & Wolfe, 2007; Diamond, 2002; Diamond et al., 1997; Luria, 1973; Passler, Isaac, & Hynde, 1985). Despite direct calls for work focusing on neural correlates of EF development, including inhibitory control and other processes (Diamond, 2002; Diamond et al., 1997; Reznick, 2007), there remain few empirical investigations directly exploring the biobehavioral expression of inhibitory control in early development.

Previous work in our research program has demonstrated that individual differences in EEG activity recorded from frontal scalp locations during inhibitory processing are associated with performance on infant and preschool-aged tasks requiring inhibitory function (for a

review, see Bell & Morasch, 2007). Task-related changes in EEG power values from a resting baseline are hypothesized to reflect changes in cortical functioning associated with task performance (Pivik et al., 1993). Indeed, in an assessment of 8-month-old infants, task-related changes in EEG activity were exhibited only by infants with high performance on a visuo-spatial task of infant inhibitory control (the looking version of the A-not-B task), whereas infants with less developed inhibitory skills exhibited no changes in EEG power values from baseline to task (Bell, 2001).

Similar patterns were detected in studies examining the biobehavioral expression of inhibitory control in two samples of 4- and 4 ½-year-olds. Again, children with better performance on preschool tasks of inhibitory control (i.e., the Day/Night task and the yes/no Stroop) demonstrated baseline-to-task changes in EEG power at the medial frontal region (assumed to reflect prefrontal cortex activation), whereas preschoolers who performed poorly on the task showed no task-related changes in EEG power (Wolfe & Bell, 2004, 2007).

Diamond (2002) stated that less is known about frontal functions from ages 1 to 3 years than during any other period of life. This is unfortunate because, as discussed above, the toddler period is a time when many advances are being made in cognitive and regulatory behavioral skills, particularly in inhibitory processes. It is likely that these developments reflect changes in brain anatomy that are known to take place in early development (i.e., growth in brain weight, increased myelination, glucose utilization, synaptic growth; Van Baal, De Geus, & Boomsma, 1996). The scarcity of electrophysiological examinations of inhibitory control development is further intriguing as EEG is one of the more favorable methodologies for brain imaging investigations with young populations (Casey & de Haan, 2002). Thus, a biobehavioral investigation of toddler inhibitory control has the ability to significantly inform the developmental cognitive neuroscience literature. Based on previous work with very young children, it is clear that not all toddlers are likely to accept the placement of physiological electrodes (Stifter et al., 1999; Wolfe & Bell, 2007). Therefore, generalizations of biobehavioral findings in our study will be cautiously discussed.

Hypothesis

We hypothesized that patterns of change in EEG power during an inhibitory control task, as well as concurrent task performance, would be related to maternal report measures of day-to-day inhibitory control functioning in toddlerhood.

Method

Participants

Eighty-one toddlers (43 boys, 38 girls; 74 Caucasian, 4 African-American, 1 Asian, and 2 Hispanic) and their mothers who were participating in a longitudinal study examining cognition-emotion integration in early development visited the research lab soon after their 2-year birthdays. All toddlers were seen between 24 and 27 months of age ($M = 25$ months, $SD = 18$ days), so that only 3 months separated the youngest and oldest children. All toddlers were born within two weeks of their expected due dates and had no diagnosed neurological problems or developmental delays. All parents completed a high school education, with 76% of parents having a college degree. Average maternal age at birth was 30 years (range 22–38) and average paternal age was 33 years (range 25–52). Toddlers were given a small gift for participation in the study.

General Procedure

Prior to visiting the research laboratory, mothers were mailed the ECBQ and MacArthur-Bates Communicative Development Inventory (MCDI) and were asked to complete them at home. Upon arrival to the laboratory, the experimenter greeted the toddler and parental consent and toddler verbal assent were obtained. The experimenter engaged the child with age-appropriate toys to help the toddler acclimate to the research lab and build a rapport with the experimenter. After this period, the application of EEG electrodes occurred. While continuous EEG was recorded, toddlers completed the conflict task, A-not-B task with invisible displacement. Following this task, the compliance assessment was recorded and EEG electrodes were then removed. Finally, the crayon delay task was administered. Each of these assessments is described in more detail below.

Laboratory-based Measures

Conflict task: A-not-B with invisible displacement—A looking version of the A-not-B task with invisible displacement was adapted to assess toddler inhibitory abilities under conditions of conflict. Originally devised by Piaget (1952), and standardized for laboratory measurement in toddlerhood by Diamond and colleagues (1997), the invisible displacement task requires toddlers to remember where a container hiding an attractive reward is located (working memory) and to inhibit responding based on the location of previous rewards (inhibitory control).

This task shares many aspects with the classic infant A-not-B task (also comparably adapted to a visual search version for use with concurrent EEG; Bell, 2001, 2002; Bell & Adams, 1999). While continuous EEG was recorded, toddlers watched as an attractive item (a red bouncy ball) was displayed and then hidden at a central location under an opaque plastic cup. The cup and hidden ball were then shifted to one side (Side A- counterbalanced left/right) of the testing table located approximately 2 m away from the toddler seated in the high chair. An opaque barrier (white foam board; 71.12 cm x 28.58 cm) was then placed in front of the cup and a 5-second delay was imposed. The experimenter distracted the toddler and kept his or her gaze at midline during the delay by enthusiastically counting aloud to five. During the delay, and behind the barrier, a second cup (hiding location B) was placed upon the table (12 inches beside the first location). The barrier was then removed and the toddler was allowed to visually search when asked, “Where’s the ball?”. First look towards either location was coded for accuracy. If the toddler accurately identified the hiding location, a second same-side trial followed. Once the toddler achieved two consecutively correct same-side findings, the hiding location was reversed (pattern AAB) to provide an inhibitory challenge. Invisible displacement performance on the task was calculated as the proportion of correct searches (Diamond et al., 1997).

Inhibitory control delay task: Crayon delay—The procedures for the crayon delay task are based on those described by Calkins (1997). At the beginning of the task, the experimenter handed the mother a magazine with a note taped to the front cover instructing the mother to appear “busy” by reading the magazine and to minimize her responses to her toddler’s attempts to initiate conversation during the delay period. The experimenter then placed a newly opened box of crayons on the table along with a blank half sheet of paper. While placing these items in front of the toddler, she asked the toddler to help her draw a picture with the new crayons. However, before the toddler could touch the crayons the experimenter told the toddler that she had to step out of the room to find something. She clearly instructed the toddler to not touch the crayons, box, or paper until she returned to the room. As she stood to leave, she reminded the toddler not to touch the crayons until she returned. The experimenter then left the room for 60 seconds. Toddlers’ behavior during the delay was scored as latency (sec) to touch the box of crayons. This task is considered

appropriate for use with toddlers and is a typical task of behavioral regulation (Calkins, 1997; Calkins & Johnson, 1998; Vaughn, Krakow, & Kopp, 1984).

Inhibitory control compliance task: Electrode acceptance—Based on work from Stifter and colleagues examining heart rate electrode placement and inhibitory control compliance in toddlerhood (Stifter et al., 1999), acceptance of EEG electrodes was recorded. With the toddler seated in a highchair next to the mother, a research assistant entertained and distracted the toddler with attractive and engaging toys. Soon after, the experimenter approached the child and displaying the EEG cap and explaining that the child would wear the cap and play some games. As described below in more detail, acceptance of the EEG electrodes involved placing the cap on the child's head, inserting the conductive and abrasive gels, testing for impedances, and required the child to continue to wear the cap throughout the behavioral protocol. Following the administration of the last behavioral task, acceptance vs. rejection of the electrodes (at any point during the protocol) was nominally coded.

Maternal-Report Measures

Temperament-based inhibitory control—The ECBQ (Putnam et al., 2006) was administered to establish a temperament-based report of toddler inhibitory control. Although all ECBQ temperament subscales were collected, the inhibitory control subscale was of particular interest in the current study. This 12 item scale had high internal consistency ($\alpha = .88$). Mothers rated their agreement with how accurately each item described their child's behavior (1= extremely untrue; 7= extremely true) in the two weeks prior to the laboratory visit. The questionnaire was mailed to mothers in advance and was collected upon arrival at the laboratory.

Verbal ability—The MCDI "Words and Sentences" form was administered to examine verbal abilities in our sample (Fenson et al., 1992). The MCDI, designed for use with 16- to 30-month-olds, is an inventory of common words and phrases. This inventory has high internal consistency ($\alpha = .96$) and has strong documented test-retest reliability ($\alpha > .90$ for all ages tested during the toddler period; Fenson et al., 1992). Mothers indicated their toddler's production of the items on the inventory (words scale) and they report their child's early grammatical ability, specifically, the complexity of multi-word utterances. The measure of interest in the current study was the percentile score associated with vocabulary production within gender.

Physiological Measures

EEG recordings—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 cognition-emotion interactions in early development. Recordings made during the conflict-inhibitory task (invisible displacement) are described and reported in the current study.

EEG recordings were made from eight left and eight right scalp sites: frontal pole (Fp1, Fp2), medial frontal (F3, F4), lateral frontal (F7, F8), anterior temporal (T3, T4), posterior temporal (T7, T8), central (C3, C4), parietal (P3, P4), and occipital (O1, O2). All electrode sites were referenced to Cz. EEG was recorded using a 21-lead stretch cap (small sized Electro-Cap) with electrodes placed in the International 10/20 system pattern (Jasper, 1958). Following 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. A small amount of abrasive (NuPrep) gel was placed into each recording site and the scalp site 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 and bandpassed from .1 to 100 Hz. Activity for each lead was displayed on the flat-screen monitor of an acquisition computer located in the control room. The EEG signal was digitized online at 512 samples per second for each channel so that the data were not affected by aliasing.

The 6–9 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 6–9 Hz band has been shown to discriminate successful and unsuccessful overall cognitive performance (Bell, 2001) as well as individual correct and incorrect responses (Bell, 2002) on an infant spatial working memory task (looking A-not-B) during the second half of the first year. EEG activity within this band also revealed performance-related differences in a sustained attention task in a cross-sectional study of 8- and 11-month-old infants (Orekhova, Stroganova, & Posikera, 1999). In infancy, the 6–9 Hz frequency band shares some qualities with those 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 inhibitory-related differences on a toddler working memory task.

During the electrode application, a research assistant entertained and distracted the toddler by playing with age-appropriate toys. This entertainment period also served to help the toddler to “warm-up” to the laboratory setting. EEG electrodes were applied and resting physiology was recorded as the toddler sat in a high chair. Toddlers watched a 60-second segment of a neutral cartoon that provided a period of physiology containing comparable eye movements and gross motor artifact to what was exhibited during the working memory test. Event marks were placed on the physiological record so that the EEG recordings could be synchronized with the stimulus presentations, hiding, and toddler choice during the task. After the A-not-B task, the EEG cap was gently removed and the gels were washed from the toddler’s hair.

Data Reduction

Behavioral data—Each visit was videotaped for later coding. Trained observers coded each of the behavioral tasks, with a second observer reliability coding a 20% overlap ($n = 16$) of the sample. Due to camera placement during the task, coders were not blind to the location of the hidden objects in the A-not-B task. Scores for these tasks were highly reliable: invisible displacement ($\alpha = 0.86$), crayon delay ($\alpha = 0.89$) and electrode acceptance ($\alpha = 1.00$). Disagreements in coding were discussed, with final determination of the score made by the first author.

Electrophysiological data—EEG data were examined and analyzed using software developed by James Long Company (Caroga Lake, NY). First, the data were re-referenced offline via software to an average reference configuration. This average referencing weighed all the electrode sites equally and eliminated the need for a noncephalic reference (Hagemann, Naumann, & Thayer, 2001). The data were then artifact-scored for eye movements using a peak-to-peak criterion of 100 μ V or greater. Artifact associated with gross motor movements over a 200 μ V peak-to-peak criterion was also scored. These artifact-scored epochs were eliminated from all subsequent analyses. The data were then analyzed with a discrete Fourier transform (DFT) using a Hanning window of 1-sec width

and 50% overlap. Power values were computed at each scalp site during each task within the 6- to 9-Hz frequency band. Power was expressed as mean square microvolts and the data were transformed using the natural log (ln) to normalize the distribution. In the case that an electrode pair was removed from analysis, due to electrical failure or high signal impedance, missing EEG power values were imputed. Replacement values were calculated as the average power value of the two most proximal ipsilateral scalp sites to the missing electrode summed with the averaged deviation from these two neighboring scalp sites. This method accounts for individual variation in EEG power values, hemispheric differences, and regional patterns from anterior to posterior across the scalp.

Results

Relations between Laboratory-Based and Temperament-Based Inhibitory Control

In our examination of the relations between laboratory- and temperament-based measures of inhibitory control, we first report mean performance of all inhibitory control measures as well as toddler verbal ability. This is followed by an analysis of the zero-order correlations among these variables. Finally, a multiple regression was conducted to examine the relations between laboratory- and temperament-based measures of inhibitory control and verbal ability.

Given a recently published meta-analysis indicating moderate effects of gender on inhibitory control (Else-Quest, Hyde, Goldsmith, & Van Hulle, 2006; where girls display more inhibitory ability), we examined gender-related differences on all inhibitory control measures, as well as language and EEG power values. Independent groups *t*-tests were conducted for all measures of interest and revealed no effects of gender (all *t*'s ≤ 1.87 , all *p*'s ≥ 0.07). Thus, gender was not included in subsequent behavioral or biobehavioral analyses.

Mean scores of each of the inhibitory control measures, as well as toddler verbal ability, are displayed in Table 1. Of the original 81 participants, two were missing A-not-B data due to fussiness, and two were missing crayon task data (one due to video-recording failure, one due to fussiness). Additionally four toddlers were missing ECBQ data and three were missing MCDI data because completed questionnaires were not returned.

In addition, zero-order correlations of temperament-based and laboratory-based inhibitory control, as well as toddler verbal ability, are displayed in Table 2. Higher maternal ratings of temperament-based inhibitory control were associated with better conflict performance (proportion of correct trials on the A-not-B task with invisible displacement), delay performance (latency to touch on the crayon task), and with higher verbal ability (percentile rank). Additionally, independent samples *t*-tests were conducted to examine compliance-related differences on the other inhibitory and language measures. Toddlers who rejected the electrodes differed from those who accepted electrodes throughout the visit only on maternal ratings of inhibitory control ($t(75) = -2.13$, $p = 0.04$). Mothers of toddlers who accepted EEG electrodes throughout the procedures rated their children as having higher temperamentally-based inhibitory control ($M = 4.15$, $SD = 0.87$) than did mothers of toddlers who rejected electrodes ($M = 3.69$, $SD = 0.75$). There were no compliance group differences on the conflict or delay measures of inhibitory control or the assessment of verbal ability (all *t*'s ≤ 0.58 , all *p*'s ≥ 0.56).

Table 3 provides the results from the regression analysis investigating relations between laboratory-based and temperament-based measures of inhibitory control, and toddler verbal ability for the 73 toddlers with complete data on these measures. Together, the three dimensions of inhibitory control (conflict, delay, and compliance) as well as toddler verbal

ability accounted for 29% of the variance in maternal-report of temperament-related inhibitory control ($F(4, 68) = 6.96, p < 0.001$). The model confirmed that verbal ability was a significant predictor of temperament-based inhibitory control, uniquely accounting for 12% of the variance in maternal report. Additionally, conflict-related inhibitory control and compliance were significant predictors of temperament-based inhibitory ability, each accounting for an additional 4% of the variance. Performance on the delay-related task of inhibitory control was not a unique predictor of temperament-based inhibitory control.

Biobehavioral Examination of Inhibitory Control

To test our hypothesis that patterns of change in EEG power during an inhibitory control task would be related to temperament-based measures of day-to-day inhibitory control functioning in toddlerhood, we conducted a multiple regression analysis exploring relations between regional EEG changes from baseline-to-task, concurrent performance on the inhibitory control task, and temperament-related inhibitory control.

Because not all toddlers accepted the EEG electrodes (20 toddlers (25%) rejected the EEG cap throughout procedures), electrophysiology was available for the remaining 61 toddlers. Additionally, three toddlers' EEG recordings were eliminated from this analysis due to missing behavioral data. This left the final sample size available for the biobehavioral analysis at 58 toddlers. As noted above, this subset of toddlers who accepted the electrodes was scored as higher on the maternal-report measure of inhibitory control than toddlers who rejected the electrodes¹.

Because rejection of the electrodes, conceptualized here as low compliance, resulted in a subset of toddlers, we repeated the previous regression analysis with these toddlers. These data are presented in Table 4. As compliance was used as a sorting dimension, it was removed from the regression equation. Similar to the analysis of the whole sample, the dimensions of inhibitory control (conflict and delay) as well as toddler verbal ability together accounted for 34% of the variance in maternal-report of temperament-related inhibitory control ($F(3, 52) = 8.81, p < 0.001$). The model confirmed that verbal ability was a significant predictor of temperament-based inhibitory control, uniquely accounting for 14% of the variance in maternal report. Additionally, conflict-related inhibitory control was a significant predictor of temperament-based inhibitory ability, accounting for an additional 9% of the variance in this subset of participants. Performance on the delay-related task of inhibitory control was again not a unique predictor of temperament-based inhibitory control.

Prior to the biobehavioral regression analysis, Pearson correlations were calculated to establish whether inhibitory task performance was associated with changes in baseline-to-task changes in EEG. Changes in EEG power at lateral frontal region (F7/F8) were related to inhibitory task performance ($r(60) = 0.23, p = 0.05$), however, there were no correlations between task performance and EEG power at other scalp locations (all r 's < 0.20 , all p 's > 0.13).

Table 5 provides the results from the regression analysis investigating relations between patterns of change in EEG power during an inhibitory control task and temperament-based measures of inhibitory control functioning in toddlerhood, as well as concurrent performance on the inhibitory control task. Together, the task-related inhibitory control performance, as well as changes in baseline-to-task related EEG from all regions, accounted for 29% of the variance in maternal-report of temperament-related inhibitory control ($F(9, 48) = 2.19, p = 0.04$). The model confirmed that task performance was a significant predictor

¹Independent-groups *t*-tests were conducted to examine other compliance-related differences in temperament. There were no compliance-group differences on any other ECBQ subscale (all t 's $\leq 1.69, p$'s ≥ 0.10) or factor (all t 's $\leq 1.31, p$'s ≥ 0.19).

of temperament-based inhibitory control, uniquely accounting for 8% of the variance in maternal report. Additionally, task-related changes in lateral frontal EEG power (F7/F8) were predictive of temperament-related inhibitory control, accounting for 7% of the variance.

Discussion

This study explored behavioral and physiological expressions of inhibitory control and how they relate to temperament-based reports of toddler inhibitory abilities. We focused on behavioral correlates of inhibitory control and replicated previous findings linking laboratory-based and temperament-based assessments of inhibitory control in toddlers. We also examined the neurological correlates of inhibitory control in toddlerhood and provided, to our knowledge, some of the first data to demonstrate relations between patterns of change in continuous brain-electrical activity and individual differences in temperament-based inhibitory control in toddlers.

Our findings revealed that individual performance on laboratory-based inhibitory control tasks across conditions of conflict, delay, and compliance was associated with temperament-based ratings of toddler inhibitory control. In addition, maternal-report of inhibitory control was related to toddler verbal ability. Specifically, toddlers who were rated by mothers as having more developed inhibitory abilities across day-to-day situations were typically able to demonstrate these abilities when faced with laboratory-based inhibitory challenges.

The fact that the tasks assessing each of these conditions (conflict: invisible displacement, delay: crayon delay task, and compliance: electrode acceptance) were related to the maternal ratings of inhibitory control, but were not correlated with one another, highlights the important information that temperament contributes to our understanding of inhibitory control specifically and EF development in general. These global ratings, completed by a highly-informed, highly-invested observer, seem to reflect the multi-faceted nature of inhibitory abilities that are particularly salient during toddlerhood. Of course, maternal-reports of temperament-based inhibitory control require repeated observations across multiple situations and circumstances. Our laboratory-based assessments of inhibitory control were short, administered only once, and were designed to explore inhibitory control outside of emotionally distressing situations, a control often not available in day-to-day life with a toddler. Therefore, it may be that maternal-reports of inhibitory abilities, at least in toddlerhood, contribute powerful information about executive abilities that individual laboratory-based tasks cannot fully capture. Thus, inhibitory abilities may serve an organizing function for several domains of toddler behavior, and conceptually, the construct of inhibitory control may integrate classic conceptualizations of temperament and higher-order cognitive and self-regulatory abilities (EF), especially within the toddler period.

Individual performance on the laboratory measures assessing inhibitory control were not intercorrelated in this sample. This is not a unique finding in early development. Vaughn et al. (1984) examined relations between the ability to inhibit during a delay challenge and to participate in a compliance task (cleaning up toys) across the toddler period. Although there were moderate positive associations between these abilities at 18 and 30 months of age, 24-month-olds showed no relation between compliance (with or without negative affect) and inhibitory ability to resist touching an attractive item during a delay (Vaughn et al. 1984). This lack of association held across three different delay tasks as well as an aggregate delay score. Similarly, Carlson and Moses (2005) administered an inhibitory control battery to 3- and 4-year-old children. Examining relations between individual tasks, investigators found that performance on measures of spatial conflict and the Day/Night Stroop-like task (Diamond et al., 1997; which requires the inhibition of a prepotent response in the face of

conflicting information) were not associated with performance on a delay task (gift delay). Indeed, a principle-components analysis produced two unique factors: Conflict (comprised of six items) and Delay (comprised of four). Interestingly, after aggregating the tasks to create these two factors, the two scales were moderately correlated ($r = 0.46$; Carlson & Moses, 2005). Perhaps with a larger battery of tasks assessing performance within the same dimensions of inhibitory abilities, latent variables underlying the different aspects of inhibitory ability would emerge and share variance.

Alternatively, this pattern of 2-year-old children demonstrating no associations among inhibitory tasks and older children showing inhibition across similar tasks may reflect a developmental trend. Kochanska et al. (2000) stated that as children age, the coherence of inhibitory abilities increases. Indeed, they found that in addition to individual performance on inhibitory tasks improving between 22 and 33 months of age, the coherence among the tasks was weaker at 22 months than at 33 months. Additionally, Carlson, Mandell, and Williams (2004) reported higher coherence across executive function tasks at age three than at age two. It may be that these abilities do not unify until later in the early childhood period. Because these data represent one time point in an ongoing longitudinal study across the infancy and childhood period, we plan to follow individual differences in the coherence and development of these abilities.

In addition, our analyses revealed patterns of neurological change associated with both temperament-based inhibitory control and inhibitory control task performance. Previous work in our lab has demonstrated changes in EEG power to be associated with task performance during infancy (Bell, 2002; Morasch & Bell, 2009) and early childhood (Wolfe & Bell, 2004). Maternal ratings of inhibitory control were related both to concurrent task performance and changes in EEG power. Specifically, correct proportional performance on the conflict task as well as baseline-to-task decreases in lateral frontal EEG power accounted for a significant amount of variance in inhibitory control.

This pattern of EEG change during the conflict task bridges the gap in similar work from our research lab conducted with infants (Bell, 2001) and preschoolers (Wolfe & Bell, 2004). Infants who succeed on a visuo-spatial task of executive function requiring inhibitory control (the A-not-B task) show a “whole head” effect, that is, EEG power values at all scalp sites change from baseline-to-task. However, preschool-age children who succeeded on tests requiring inhibition of a dominant response demonstrated performance-related changes in EEG power only at medial frontal scalp sites (Bell & Wolfe, 2007). Therefore, the current results, showing change at the lateral frontal scalp regions, may reflect increasing specificity of the neurological underpinnings of inhibitory control across the second year of life.

These data represent the first simultaneous exploration of inhibitory control and continuous EEG in toddlerhood. Care must be used, however, when generalizing and interpreting these biobehavioral results. As previously stated, these physiological data were collected from a subset of toddlers whose inhibitory abilities were developed to the point that they could comply with this unique method of data collection. Within this sample, individual differences in inhibitory control related to temperament were linked to regional brain-electrical activity, such that higher maternal ratings were related to larger changes in EEG power values from baseline-to-task. Because physiology was not available for toddlers who rejected the electrodes (i.e., toddlers who displayed less developed inhibitory control under compliance conditions), it is difficult to hypothesize what physiological patterns might underlie global ratings for toddlers in this low-inhibitory control subset. Thus, one limitation of this study is that no physiological information was available for the most noncompliant toddlers. Future psychophysiological investigations with this age-group may benefit from the inclusion of electrocardiogram (ECG) recordings, which involve less demanding

procedures for use in developmental populations, and can contribute to knowledge about the reactivity and self-regulatory components inherent to the study of inhibitory abilities.

As previously stated, these data were collected during one time point of a longitudinal investigation exploring the integration of cognition and emotion beginning in infancy and continuing into childhood. We plan to investigate the longitudinal trajectories of EF with respect to the contributions from temperament across this time period, both behaviorally and physiologically. Additionally, we are interested in patterns of change throughout the early childhood period, as frontally-mediated regulatory mechanisms become prominent. Finally, we plan to explore contributions from infant and toddler physiology and behavior associated with EF to outcome measures in childhood, including school readiness and achievement.

Despite the intriguing relations among behavior, temperament, and brain-based physiological activity described in this study, the ability to inhibit behavior is a skill that not all toddlers have mastered by age two. However, it is unclear whether these individual differences in toddler inhibitory control are driven by cognitive capabilities, temperament-based foundational differences, or functional maturity of cortical regions during this time of biobehavioral transition. The development and directional testing of biobehavioral components within a model of inhibitory control development in early childhood would be a major contribution to the developmental cognitive neuroscience literature.

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Table 1
Mean Performance on the Inhibitory Control Measures and Toddler Verbal Ability

Measure	<i>M</i>	<i>SD</i>	Min	Max	<i>n</i>
ECBQ Inhibitory Control Subscale	4.02	0.86	2.50	5.92	77
Conflict: A-not-B Proportion Correct	0.65	0.24	0.00	1.00	79
Delay: Crayon Task Latency to Touch	23.46	24.89	0.00	60.00	79
Compliance: EEG Electrode Acceptance	0.75	0.43	0.00	1.00	81
Verbal Ability: Percentile Rank	55.22	29.48	5.00	99.00	78

Table 2
Zero-order Correlations among Inhibitory Control Measures and Verbal Ability

Measure	ECBQ	Conflict	Delay
Conflict: A-not-B Proportion Correct	0.27*		
Delay: Crayon Task Latency to Touch	0.26*	0.18	
Verbal Ability: Percentile Rank	0.43**	0.16	0.18

Note:
* $p < 0.05$,
** $p < 0.001$

Summary of multiple regression analysis predicting temperament-based inhibitory control from lab-based inhibitory control tasks and verbal ability ($n = 73$)

Table 3

Predicted: ECBQ Inhibitory Control Subscale	B	SE(B)	β	t	p	sR^2
Conflict: A-not-B Proportion Correct	0.76	0.37	0.22	2.07	0.04	0.04
Delay: Crayon Task Latency to Touch	0.01	0.01	0.17	1.60	0.11	0.02
Compliance: EEG Electrode Acceptance	0.40	0.20	0.21	2.01	0.05	0.04
Verbal Ability: Percentile Rank	0.01	0.01	0.35	3.33	0.01	0.12

Note: $R^2 = 0.29$, $F(4, 68) = 6.96$, $p < 0.001$

Table 4

Summary of multiple regression analysis for the subsample of compliant toddlers predicting temperament-based inhibitory control from lab-based inhibitory control tasks and verbal ability ($n = 56$)

Predicted: ECBQ Inhibitory Control Subscale	B	SE(B)	β	t	p	sR^2
Conflict: A-not-B Proportion Correct	1.10	0.42	0.31	2.66	0.01	0.09
Delay: Crayon Task Latency to Touch	0.05	0.01	0.15	1.30	0.20	0.02
Verbal Ability: Percentile Rank	0.01	0.01	0.37	3.22	0.01	0.14

Note: $R^2 = 0.34$, $F(3, 52) = 8.81$, $p < 0.001$

Summary of multiple regression analysis predicting temperament-based inhibitory control from lab-based inhibitory control tasks and verbal ability ($n = 58$)

Table 5

Predicted: ECBQ Inhibitory Control Subscale	B	SE(B)	β	t	Sig. (p)	sR^2
Conflict: A-not-B Proportion Correct	1.09	0.46	0.30	2.40	0.02	0.08
Task-Related Changes in EEG Power						
Frontal Poles (Fp1, Fp2)	0.28	0.53	0.09	0.52	0.61	0.00
Medial Frontal (F3, F4)	0.27	0.69	0.09	0.39	0.70	0.00
Lateral Frontal (F7, F8)	-1.45	0.66	-0.39	-2.19	0.03	0.07
Central (C3, C4)	0.02	0.33	0.01	0.07	0.94	0.00
Anterior Temporal (T3, T4)	-0.09	0.50	-0.03	-0.19	0.85	0.00
Posterior Temporal (T7, T8)	0.64	0.57	0.18	1.12	0.27	0.02
Parietal (P3, P4)	0.52	0.45	0.21	1.16	0.25	0.02
Occipital (O1, O2)	0.25	0.50	0.08	0.50	0.62	0.00

Note: $R^2 = 0.29$, $F(9, 48) = 2.19$, $p = 0.04$