

Trajectories of infants' biobehavioral development:  
Timing and rate of A-not-B performance gains and EEG maturation

Leigha MacNeill,<sup>1</sup> Nilam Ram,<sup>2</sup> Martha Ann Bell,<sup>3</sup> Nathan A. Fox,<sup>4</sup> & Koraly Pérez-Edgar<sup>1</sup>

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<sup>1</sup>Department of Psychology, The Pennsylvania State University, University Park

<sup>2</sup>Department of Human Development and Family Studies, The Pennsylvania State University,  
University Park

<sup>3</sup>Department of Psychology, Virginia Tech, Blacksburg, VA

<sup>4</sup>Department of Human Development and Quantitative Methodology, University of Maryland,  
College Park

## Abstract

This study examined how timing (i.e., relative maturity) and rate (i.e., how quickly infants attain proficiency) of A-not-B performance were related to changes in brain activity from age 6 to 12 months. A-not-B performance and resting EEG (electroencephalography) were measured monthly from age 6 to 12 months in 28 infants and were modeled using logistic and linear growth curve models. Infants with faster performance rates reached performance milestones earlier. Infants with faster rates of increase in A-not-B performance had lower occipital power at 6 months and greater linear increases in occipital power. The results underscore the importance of considering nonlinear change processes for studying infants' cognitive development, as well as how these changes are related to trajectories of EEG power.

Infants undergo substantial changes in cognitive functioning in the second half of the first year (Bell & Fox, 1992; Cuevas & Bell, 2010; Diamond, 1985). The A-not-B task, a classic measure of cognitive development in infancy, was developed by Jean Piaget (1954) to assess 8- to 12-month-old infants' understanding of object permanence (i.e., knowledge that an object exists when it is no longer in sight). Although most infants are capable of completing the task by age 12 months, the timing and rate of progression toward successful performance differ among infants across the second half of the first year. Piaget's model of qualitative stages in cognitive development implies nonlinearity, in which the development of children's thinking is not additive, but undergoes substantial reorganization over time (van Geert, 1998). Previous work indicates that task performance is related to variation in brain structure and function. For example, rhesus monkeys with bilateral ablations of the dorsolateral prefrontal cortex make the A-not-B error at varying delays whereas monkeys without these lesions do not (Diamond & Goldman-Rakic, 1989). Prior research with human infants suggests positive associations between frontal electroencephalogram (EEG) power and object permanence task performance (Bell & Fox, 1992). These findings, among others, illustrate that advancements in children's cognitive performance may parallel concurrent changes in the brain (Fischer & van Geert, 2014).

The literature highlights the presence of individual differences in infants' development of object permanence, particularly when assessing the amount of delay necessary to evoke the A-not-B error (Bell & Fox, 1992; Diamond, 1985). However, age-related changes in A-not-B task performance, as a nonlinear developmental process, have not yet been charted. Moreover, questions still remain concerning whether or how changes in EEG power map onto children's cognitive development in general, and in the A-not-B task specifically. The current study used linear growth models with logistic model parameters as predictors to examine the relation

between timing (i.e., relative maturity) and rate (i.e., how quickly infants attain proficiency) of A-not-B performance gains from 6 to 12 months of age. In turn, we mapped performance changes onto age-related changes in baseline EEG power.

### **The A-not-B Error**

In 1954, Jean Piaget published work on the development of the object concept, or the understanding that objects exist as unique entities outside of one's own actions (Piaget, 1954). This skill is thought to be obtained little by little across the six substages of sensorimotor development, and it was argued that children do not conceptualize the object as having its own pattern of movement that is both distinct from the child and is also predictable and logical until the second year. Piaget was among the first scientists to investigate children's attainment of the object concept, or object permanence, arguing that this knowledge is the essential groundwork for building subsequent knowledge of the physical world. He believed that the intellectual structures of the child change through stages, and that each of these stages is qualitatively different from the stages that had come before (Flavell, Miller, & Miller, 1993).

In the 60-plus years since these original observations took place, researchers have investigated the underlying skills necessary to correctly display mastery of object permanence. Arguably, one of the tasks most often used to measure object permanence is Piaget's own A-not-B task (1954). In this task, an attractive object is hidden at one location (*A*) multiple times in front of the infant until it is switched to another, adjacent location (*B*). Further, the experimenter may impose a time delay between hiding the object at *B* and allowing the infant to search. The A-not-B error lies in the infant reaching toward *A*, despite having seen the object's placement at *B*.

There are numerous explanations as to why infants make the A-not-B error, and the skills necessary to perform the A-not-B task successfully may extend beyond the simple acquisition of object permanence. Diamond (1985) has demonstrated that as infants get older, the length of delay between hiding the object and allowing the child to search for the object must increase for infants to make the perseverative error. This work has established the A-not-B task as a marker of the infant's ability to remember previous events, coupled with the ability to inhibit a prepotent motor response to form a correct response. The data also imply that the infant's actions are governed by their intention, as opposed to a developed habit. Diamond (1990) later proposed that both the integration of recall memory and the inhibition of a prepotent response are jointly necessary for solving the A-not-B task. Wellman, Cross, and Bartsch (1986) posited that the infant must have an understanding of how objects move in space, so that they may infer an object's current location after tracking its movement from one location to the next.

Current conceptualizations contend that the task can be interpreted as an early measure of children's executive function (Diamond, 2006). The delays between hiding the object and allowing the infant to search can be taxing on infants' memories, thus age-related change in A-not-B task performance may be indicative of improvements in the capacity and duration of working memory (Marcovitch & Zelazo, 1999). Smith and colleagues proposed that in order for the infant to correctly obtain the object at the second location, infants need to be able to discriminate locations that look similar as well be able to reach for the object (Smith, Thelen, Titzer, & McLin, 1999). Building on the large perceptual changes that co-occur with enhanced locomotor skills in the second half of the first year, infants are able to couple their looking and reaching abilities, such that each discrimination and reach emerges from memories of previous discriminations and reaches (Smith et al., 1999). The A-not-B error thus may not necessarily

represent a failure to obtain object permanence, insomuch that it demonstrates the difficulty of keeping an object's new location in mind when exerting control over a motor response. Building on the various interpretations of the constructs underlying the A-not-B task, we argue that the task taps the intersection of infants' object permanence, executive functioning, and working memory. Additionally, we agree with the consensus that the task also requires flexibility in infant cognition and the deployment of motor behavior (e.g., Clearfield, Diedrich, Smith, & Thelen, 2006; Diamond & Doar, 1989; Smith et al., 1999). The current paper examines growth in A-not-B performance in light of changes in EEG power in an intensive longitudinal sample. This foundational work points to potential mechanisms for further study and illustrates the use of emerging analytical techniques in the study of early cognitive development.

Given the number of skills required to successfully perform the A-not-B task at varying delays, it comes as no surprise that there are both interindividual and intraindividual variability in infant performance. Diamond (1985) found large between-subject differences in the delay at which same-age children made the A-not-B error from when they first began reaching for the object until 12 months of age. Additionally, her work demonstrated that infants persisted in making these errors until 12 months of age with increases in delay. Other work has found that by 8 months of age, performance on the A-not-B task is normally distributed, such that there was a wide range of performance scores with a mode of 3 on a scale from 1 to 6 (Bell & Adams, 1999). One aim of the current study was to examine individual differences in A-not-B task performance from 6 to 12 months of age using logistic parameters to capture nonlinearities in this development.

### **The Role of Brain Development in A-not-B Performance**

Differences in individual task performance may be associated with brain activity over this developmental window (Bell, 2001, 2012; Bell & Fox, 1992, 1997; Cuevas & Bell, 2011; Cuevas, Bell, Marcovitch, & Calkins, 2012) and may point to mechanisms underlying variation that occurs in the development of infants' task performance (Fischer & Rose, 1997). Fischer and van Geert (2014) argued that changes in the rapidly maturing brain underlie the quick bursts and discontinuities in behavior and the presumed knowledge base of the developing infant. Early in development, neurons that are relatively unused are pruned in order to increase neural efficiency (Huttenlocher & Dabholkar, 1997).

With efficiency also comes the coordination of neural systems involved in newly emerging behaviors, as in mastering object permanence and the related skills needed to overcome the A-not-B error. Sustaining multiple actions, such as tracking a moving object and keeping it in mind as it is relocated, while also inhibiting the prepotent response of reaching at the previous location, are action systems that must be coordinated for successful performance (Fischer & van Geert, 2014). The prefrontal cortex plays a role in holding this type of information in the moment while the individual engages in other actions (Thatcher, 1994). Diamond (1988, 1990) argued that frontal functioning promoted necessary skills such as recall memory and inhibition. Additionally, the prefrontal cortex actively changes in infancy, as lateral portions of the frontal cortex increase in glucose metabolism in the dorsal prefrontal area at 8 months versus 3 months in the temporal lobes (Chugani, 1994). Because the A-not-B task involves the ability to attend to visual stimuli and track moving objects in space, we may also expect to see development of the occipital region in concurrence with A-not-B development. Occipital power has been positively related to cognitive performance in infants (Bell & Fox,

1997), and visual processes demonstrate greater environmental awareness by the end of the first year (Fox et al., 1979).

Much of the research on early brain development has utilized electroencephalography (EEG), which is a noninvasive measurement tool designed to assess electrical activity in the brain (Pizzagalli, 2007). EEG has the temporal resolution to capture quick shifts in brain functioning that may parallel the rapid cognitive processes that unfold on the order of milliseconds (Bell, 1998). The dominant frequency band during baseline recordings in infancy is the 6- to 9-Hz alpha band, identified by the small-band method measuring each spectra and frequency band within the peaks in the spectrum (Bell & Fox, 1992; Marshall, Bar-Haim, & Fox, 2002). Stoganova and Orekhova (2007) have labeled the 6- to 9-Hz frequency range as alpha, and it is considered a gold standard for EEG research in infancy. The 6- to 9-Hz band has been examined during inhibitory control (Morasch & Bell, 2011; Orekhova, Stroganova, & Posikera, 2001) and working memory (Cuevas et al., 2012) tasks. EEG power values are thought to characterize excitability in a cluster of neurons and are combined across individual 1-Hz frequency bins to indicate power measurement in a specific frequency band in infancy. Research suggests that increases in EEG power in the alpha 6- to 9-Hz frequency band reflect more neural activity, and this neural activity has been associated with increased cognitive skill in infancy. Developmental neuroscientists also consider higher EEG power to be indicative of broad brain development, as previous work has found linear increases in power across infancy and that higher power values are related to increased cognitive performance (Bell & Fox, 1992; Cuevas & Bell, 2011).

How EEG power changes over time, and how it relates to behavior over time, are dependent upon the type of cognitive process and frequency band being assessed. Studies on

event-related desynchronization and synchronization, with a focus on alpha-band activity, examine event-related power responses from baseline assessments to attention and memory tasks with infants and adults. Whether EEG power is positively or negatively related to cognitive processing in infants and adults is dependent on the type of cognitive processing the task requires (Klimesch, 2012). Increases in baseline EEG power, in particular, are thought to reflect extensive organization of neurons (Nunez, 1981). Linear increases in baseline power are evident across the scalp at frontal, parietal, and occipital sites from 7 to 12 months of age in the 6- to 9-Hz frequency band, with the greatest increase between 9 and 10 months (Bell & Fox, 1994). Mizuno and colleagues' (1970;  $N = 10$ ) study was one of the first to demonstrate increases in baseline alpha activity (6-9 Hz) between 7 and 12 months at all electrode sites. Thus, in the current study, it was hypothesized that baseline power would increase over time.

The association between performance on working memory tasks and increases in baseline EEG power has also been established in the literature. Bell and Fox (1992) found that baseline EEG power increased monthly in the 6- to 9-Hz range from 7 to 12 months of age and demonstrated that changes in frontal power were associated with greater delay tolerance on the A-not-B task. Bell (2002) tested 8-month-old infants on a spatial working memory task and assessed EEG power in the 3- to 5-Hz, 6- to 9-Hz, and 10- to 12-Hz frequency bands both at baseline and during the task. She found that the 6- to 9-Hz band yielded differences in baseline and task power values, demonstrating increased power during the cognitive task. In addition, 8-month-old infants who successfully completed the looking version of the A-not-B task tolerating a 0-second delay or greater demonstrated increases in frontal, parietal, and occipital power in the 6- to 9-Hz frequency band from baseline to task performance. However, there was no increase in power for the children who did not complete the task correctly (Bell, 2001). Greater EEG power

at frontal and occipital locations during baseline recordings prior to task performance were associated with better performance on the A-not-B task (Bell & Fox, 1997).

In the reaching version of the A-not-B task we can only rely on baseline EEG given that task-linked movements lead to excessive signal artifact (Bell, 2001). Eight-month-old infants who performed successfully on the A-not-B task with a 0-second delay or greater demonstrated greater medial frontal and occipital baseline EEG power in the 6- to 9-Hz frequency band than children who did not successfully complete the task (Bell & Fox, 1997). These results underscore the evidence for scalp-wide increases in baseline power for infants who successfully performed the task compared to infants who did not. In the current study, it was therefore predicted that increases in baseline EEG power over the second half of the first year would be associated with advancements in A-not-B task performance.

To date, little research has longitudinally assessed both A-not-B task performance and the associated markers of neural development monthly. Bell & Fox (1992) examined A-not-B performance from 7 to 12 months in 13 infants and collected EEG at rest at each age. Infants who could tolerate a longer delay on the A-not-B task at 12 months of age demonstrated differential changes in frontal power development, showing a decrease between 7 and 8 months and an increase between 9 and 10 months. The group with a shorter delay period only showed an increase in frontal power between 10 and 11 months. Additionally, the two groups of infants first differed on task performance at 10 months of age, which was also the point in time when the long-delay group showed the largest increase in frontal EEG power. These findings suggest that toward the end of the first year, the relation between growth in cortical organization and object permanence ability becomes more established. The Bell and Fox (1992) paper was one of the first to establish that there is interindividual variability in A-not-B task performance, in that

infants at 12 months of age ranged in delay from 0 to 14 seconds. Although infants demonstrate remarkable and differentiated progress on both brain activity and A-not-B task performance over the latter half of the first year, the literature has yet to chart the relations across trajectories over time at the level of the individual. Therefore, one of the aims of the current study was to examine individual differences in age-related change of brain activity in relation to timing and rate of A-not-B performance gains.

### **Timing and Rate of A-not-B Performance Gains**

If observed behavior and the brain are part of a dynamic network of systems that co-occur and are responsible for each other's change (e.g., Fischer & van Geert, 2014), then a necessary initial step to examining this relation is to model development in ways that best characterize how particular systems change over time and how the growth in these systems change in relation to one another. Adolph and Robinson (2008) argued that the field has been overly reliant on examining development through differences between a beginning time point and an end time point, often as a single difference score. They contended that developmental systems frameworks should aim to explain processes of change and the shape of the change across time. Additionally, development does not unfold in steady increments. Rather, it speeds up and slows down at different points in time (Fischer & Rose, 1997; Thatcher, 1994). Research on infant development is often characterized by spurts in behavior that could be due to distinct developmental processes, such as verbal or spatial skills and differences in brain activity. The coordination of these behaviors is reflective of clusters of discontinuities from which new behaviors can emerge (Fischer & Rose, 1997). Around 8 months, for instance, multiple skills undergo sharp increases, such as crawling ability (Adolph, Bertenthal, Boker, Goldfield, & Gibson, 1997), vocal imitation (Petitto & Marentette, 1991), and object search performance (Bell

& Fox, 1994). These dramatic shifts in behavior imply nonlinearities in infant development. Although many aspects of development are described as nonlinear and dynamic processes, the empirical literature has tended toward using methods that describe stability and linear change.

Trajectories of cognitive growth can be portrayed by timing, or how mature infants are in relation to their same-age peers, and rate, or how quickly or slowly infants gain proficiency in cognitive performance. In the case of the A-not-B task, infants can be considered early, average, and late maturers contingent upon their performance of the A-not-B task relative to other infants. They are also considered as quick, average, or slow maturers, based upon the rate at which they progress from no proficiency to proficiency on the task. The current study focused on a time window (6 to 12 months) that would likely encompass the first emergence and competence of A-not-B performance. Regarding rate, there is little research explicating the rates of A-not-B performance in the first year. We know that A-not-B performance increases with age (Bell & Fox, 1992; Cuevas & Bell, 2010; Diamond, 1985; Fox, Kagan, & Weiskopf, 1979), but the rate at which A-not-B performance can progress for individual infants is still unclear.

The present study is the first to examine individual change in A-not-B performance in the second half of the first year. In the current study, we attempted to measure the potential relation between A-not-B performance and EEG power development from 6 to 12 months of age. We hypothesized that earlier timing of A-not-B task performance would be associated with higher initial level of and linear change in EEG power. We also hypothesized that faster rate of A-not-B task performance would be linked to higher initial level of and linear change in EEG power.

### **Modeling Timing and Rate of A-not-B Task Performance**

To our knowledge, A-not-B task performance in infancy has not been examined using nonlinear growth models. Although there has been research to show that successful A-not-B

performance increases over age (e.g., Bell & Fox, 1992; Cuevas & Bell, 2010; Diamond, 1985), it is likely that the shape of the trajectory of A-not-B task performance is nonlinear and more representative of a sigmoid, or “S”-shaped, curve. There are data noting the discontinuities in the development of cognitive processing, in that spurts of growth are clustered at specific points of time in the first year (Fischer & Rose, 1997). For example, infants show a steep progression in their object search performance at 8 months of age (Bell & Fox, 1994). Between 10 and 12 months, drastic differences occur in task performance as well (Smith & Thelen, 2003).

Munakata (1998) traced infants’ reaches at both A and B, finding that the percent of correct responses for reaching at A revealed a flat line between 90% and 100%. The percent of correct responses for reaching at B, however, revealed a sigmoid shape with upper and lower asymptotes. Piaget’s theory of cognitive development represents changes as discontinuous, where children’s thinking is qualitatively different at each stage (or substage) of development. Therefore, research must model development accordingly, acknowledging the potential patterns of nonlinearity in infants’ early cognitive trajectories and ages at which cognitive performance levels off. The current study used nonlinear growth curve models, a relatively novel method in the field of infant cognition, to take into account the nonlinearities that other studies have implied but have not directly tested.

Growth models provide a framework for describing the timing and rate of this change (Duncan, Duncan, Stryker, Li, & Alpert, 1999; Grimm, Ram, & Hamagami, 2011; McArdle, 2009; McArdle & Nesselroade, 2003; Ram & Grimm, 2007). Following work wherein nonlinear growth models were used to examine between-person differences in timing and rate of pubertal development (Marceau, Ram, Houts, Grimm, & Susman, 2011; Susman et al., 2010), our work examines how between-person differences in the timing and rate of infants’ performance on the

A-not-B task are related to changes in EEG power. Given that infants' capabilities change rapidly over the latter half of the first year, and that there is within-person variability in performance on these tasks, the present study investigated the timing and rate of infants' cognitive and brain growth within this important developmental time window.

The present study used linear and nonlinear growth models to relate timing and rate of A-not-B task performance to change in EEG power from 6 to 12 months of age. The chosen age range was based on Diamond's (1985; 1989) work, which assessed A-not-B task development every two weeks from 6 to 12 months of age. She found that infants began reaching for the object at 7.5 months, and they increased in delay tolerance at the average rate of 2 seconds per month. There were, however, large individual differences in the delay needed for the error at every age. Our objectives were to: (a) describe nonlinear growth trajectories in A-not-B task performance with respect to timing and rate of performance gain, and (b) examine the associations between *nonlinear* performance change and *linear* age-related changes in infants' EEG power across the second half of the first year.

## Method

### Participants

Twenty-eight healthy 6-month-old infants (14 boys, 14 girls) and their parents were recruited through mailing lists to participate in a longitudinal study of infant development. The participants were Caucasian from generally middle to upper-middle class homes in the greater Washington D. C. metropolitan area. Only infants born to two right-handed parents were selected to participate in the study. Parental handedness was assessed with the Edinburgh Handedness Inventory (Oldfield, 1971), and children of parents who received scores of at least 10 were selected for the study. Additionally, infants were chosen if they were born within three

weeks of their anticipated due date, weighed at least six pounds at birth, received no special medical intervention at birth, had no documented neurological problems, and both parents had at least a high school education. These selection criteria data were obtained over the telephone with the parents prior to their first visit.

## **Procedures**

Parents brought their infants into the laboratory every month from 6 to 12 months of age, each time within 5 days of their monthly birthday (total of 7 visits). At each visit, brain electrical activity (EEG) was recorded and the infant completed a series of cognitive tasks, including the A-not-B task.

***Electrophysiological Recording.*** Brain electrical activity was recorded during a 2-minute pre-task baseline recording session at each visit. Infants were placed in either a high chair or at a feeding table. The parent was instructed to sit slightly behind the infant and not speak to the infant unless the infant was distressed and they needed to soothe the infant. During the recording, the infant watched the experimenter spin balls in a bingo wheel, segmented into 10 seconds of spinning 1, 3, and 7 balls, each separated by a 10 second pause, and then the 1-3-7 sequence with pauses repeated. Power values were yielded at each electrode site for each stimulus condition (spin 1, spin 3, spin 7, pause), resulting in a composite of EEG baseline power values that were used in the current analyses.

EEG recordings were taken from six scalp placements referenced to Cz: left and right frontal, parietal, and occipital regions (F3, F4, P3, P4, O1, and O2). These scalp sites were chosen to represent electrical activity from anterior to posterior parts of the scalp. Channels A1 and A2, located at the ears and referenced to Cz, were also recorded. Recordings were captured using an Electro-Cap stretch cap with a 10/20 electrode system placement. Once the cap was

placed on the infant's head, a small amount of Omni-Prep was used to abrade the scalp with the blunt end of a Q-tip. EEG electrode gel was then inserted into each site. If sites were above 5K Ohms, additional abrasive was used. EOG was recorded from the external canthus to the supra-orbit of one eye. This channel was digitized with the EEG recordings to facilitate artifact editing.

All EEG leads, two ear leads, and the EOG lead were separately amplified by Grass Model 12A5 amplifiers as part of the Neuro-data acquisition system (Grass Model 12-32). Digitalization of data was done online using a HEM A/D board mounted in an IBM PS2/80 computer with HEM customized software. Channels were displayed on a Grass Model 78D polygraph. The EEG was digitized at 512 Hz per channel, and this high sampling rate was chosen to insure no problems aliasing the data and to examine EMG artifacts at 90- to 200-Hz. Before recording the participants, a 10 Hz .477 V rms sine wave was input through each amplifier of the polygraph. The amplifier was configured so the output of the signal was 50  $\mu$ V peak to peak with a gain of 10,000. The calibration of each amplifier was digitized for 30 seconds. The EEG data were re-referenced to an average reference configuration prior to editing.

The EEG data were edited for eye movement and gross movement artifact. Trained coders marked epochs that were corrupted by EOG or gross motor movement and these channels were thus removed from further analyses. On average, 50% of the EEG data were artifact-free at the 6-month measurement occasion, 54% at the 7-month measurement occasion, 54% at the 8-month measurement occasion, 58% at the 9-month measurement occasion, 57% at the 10-month measurement occasion, 59% at the 11-month measurement occasion, and 58% at the 12-month measurement occasion. All analyses used the artifact-free data. Individual patterns of available

EEG data were not associated with any study variables ( $p$ 's > .08). The EEG data were analyzed using a discrete Fourier transform with a Hanning window of a one-second width with 50% overlap. The mean voltage was subtracted from each data point to remove any power results due to DC offset before DFT computation. Power in single Hz bands was computed for frequencies between 1 and 12 Hz, and power was expressed in mean square microvolts. In line with longitudinal research for infants of this age, plots of spectral power indicated dominant frequency in all leads at all ages was in the 6- to 9-Hz alpha band (Marshall, Bar-Haim, & Fox, 2002). Given the positive skewness of the data, power values were log transformed ( $\ln$ ) in this frequency band. One male infant missed his 9-month visit and twelve of the participants had incomplete EEG data due to artifacts and poor channel recordings. Chi-square tests of independence suggested that children with complete and incomplete data did not differ on any of the available demographics ( $\chi^2 < 1.313, p > 0.252$ ). ANOVA tests indicated that those children with missing data at any point tended to have higher power at some EEG measurement occasions (i.e., F3 at 10 months, P3 at 8 and 9 months, F4 at 11 months, P4 at 9 and 10 months, O1 at 10 months, and O2 at 10 months) and lower at power at another (i.e., P3 at 10 months). Given the inconsistencies in these missing data patterns, it was assumed that the data were missing at random and could be handled using maximum likelihood estimation.

***A-not-B Task with Delay.*** After the electrophysiological recording, infants were assessed on the A-not-B task with delay, which was modeled after the standard two-location task (Wellman et al., 1986). The AB apparatus was a cardboard box measuring 47.5 cm (length) by 22.5 cm (width) by 7.5 cm (depth). It contained two wells, A and B, that were each 9.5 cm in diameter and 7.5 cm deep, separated by 29 cm from center to center and covered with 20 squared-cm white fabric cloths. The apparatus was positioned on the floor in front of the infant,

such that the center of the box was at midline and the wells were within reach of the infant. While the parent sat behind the infant, the experimenter sat on the opposite side of the apparatus facing the infant and parent. Given that not all toys are equally engaging among children, an assembly of toys was placed next to the experimenter. The experimenter could thus choose a toy that appealed to the infant and substitute a new toy if the infant lost interest.

The experimenter signaled the beginning of a trial by holding up a toy to engage the infant's attention. Subsequently, the experimenter lifted the cloth covering one of the wells (A or B), placed the toy in that well, and then covered the well again with the cloth, completely obscuring any sight of the toy. If attention was lost during the trial, the experimenter regained the infant's attention and hid the toy again. A correct response was coded if the child recovered the toy from side A. Also included as a correct response was uncovering the correct well but failing to reach for the toy and uncovering both wells yet visually fixating on the correct well. In prior work (Bell & Fox, 1992), this latter response was seen quite often. In order for the response to be deemed correct, both the experimenter and an observer had to have witnessed the fixation on the cloth covering the toy. Uncovering the empty well, not reaching for the toy, and not fixating on the well housing the toy were all deemed incorrect responses.

A successful trial consisted of correctly retrieving the toy from side A two times, then a correct retrieval to side B, or the second well. This trial was deemed the "A-A-B" trial. If the infant's interest in the toy waned, the experimenter selected a new toy that captured the child's attention and started the trial over. After successfully retrieving the toy in trial A-A-B, the infant had to then correctly uncover side A in trial B-B-A. If the infant did not succeed in the trial B-B-A, this trial was repeated. The initial site of hiding the toy was randomized across participants

and visits. Infants were required to recover the toy on 2 out of 3 trials in both directions (to eliminate preferential reaching) to be considered competent at the task.

The A-not-B task was scored by delay on a scale from 0 to 4. A score of “0” represented a failure to complete the task at a 0-second delay. A score of “1” represented competence at completing the task with a 0-second delay, where the infant was allowed to immediately search for the toy once it was hidden. Scores of “2”, “3”, and “4” were given when the infant completed the task with a 2-second, 4-second, or 6-second or greater delay, respectively. During the delay period, the experimenter broke the infant’s attention from the task by clapping her hands together. The parent was also told to hold the infant’s hands to prevent reaching during the hiding and delay periods. The delay period began once the experimenter observed the infant’s attention breaking from the second well. Two observers completed coding of A-not-B performance by videotape very shortly after the session took place. The principal investigator, the experimenter, and the observer in the session reviewed these codes independently to resolve any discrepancies.

### **Data Analysis**

Data analysis proceeded in two steps, organized and constructed to make efficient use of the unique study design that encompassed seven monthly repeated measurements of task behavior and brain function. We viewed our analyses of this small and very unique sample as semi-exploratory – using linear and nonlinear growth models to extract meaningful parameters from the rich and unique repeated measures data, but not claiming or assessing model fits as confirmatory evidence for statistical inference.

*Interindividual differences in development of A-not-B task performance.* Our first aim was to quantify interindividual differences in the development of infants’ A-not-B task

performance from age 6 to 12 months. The data had some distinctive characteristics that suggested description using a logistic growth function (Grimm & Ram, 2009; Ram & Grimm, 2007). By design, the A-not-B task imposes clear lower and upper bounds on performance. Theoretically, all children progress from a stage when they are not able to perform the task at a 0-second delay (performance = 0) to a stage when they perform the task at a 6-second or greater delay (performance = 4). As such, we modeled the seven,  $t = 0$  to 6, repeated observations of each infant  $i$ 's performance as

$$Performance_{it} = \theta_0 + (\theta_1 - \theta_0) \left\{ \frac{1}{1 + \exp[-r_i(\text{age}_{it} - \theta_{2i})]} \right\} + e_{it} \quad (1)$$

where  $\theta_0$  defines the lower asymptote of performance, in our case fixed = 0 (failure to complete task at 0-second delay);  $\theta_1$  defines the upper asymptote of performance, in our case fixed = 4 (A-not-B performance with 6-second or greater delay);  $\theta_{2i}$  is a person-specific coefficient that captures the *timing* of change, specifically considered here as the age at which an infant would reach a performance score = 2 (formally, the inflection point located halfway between the lower and upper asymptotes);  $r_i$  is a person-specific coefficient that indicates the *rate* at which an infant develops (i.e., rate governing change from the lower to the upper asymptote; higher rate values indicating that the infant is improving in A-not-B task performance more quickly over time at the inflection point, relative to the other infants); and  $e_{it}$  is residual error assumed normally distributed with a mean of zero and a variance  $\sigma_e^2$ . Analytically, the logistic growth model served as a “measurement model” to derive timing and rate scores ( $\theta_{2i}$  and  $r_i$ ) that could then be examined in relation to individual differences in the development of EEG power. The selection of the score of 2 provided a common point, or parameter in the model, on which to compare individuals most parsimoniously. Linearity was accommodated in the measurement scale (0 to 4). Nonlinearity was accommodated in development of cognitive performance, given the

previous research revealing nonlinearities in infants' cognitive development. Models were fit to each infant's repeated measures data by looping the nls function in R (R Core Team, 2013) with a range of starting values that facilitated convergence for all  $N = 28$  cases.

***Associations between development of EEG power and development of A-not-B task performance.*** Interindividual differences in the development of infants' EEG power from age 6 to 12 months were then modeled using a standard linear growth model with covariates (Grimm, Ram, & Estabrook, 2017). Specifically, the seven,  $t = 0$  to 6, repeated observations of EEG power were modeled, separately for each electrode location (F3, F4, P3, P4, O1, O2), as

$$EEGpower_{it} = \beta_{0i} + \beta_{1i}age_{it} + e_{it} \quad (2)$$

with the person-specific intercept and linear slope coefficients modeled as

$$\beta_{0i} = \gamma_{00} + \gamma_{01}timing_i + \gamma_{02}rate_i + u_{0i} \quad (3)$$

$$\beta_{1i} = \gamma_{10} + \gamma_{11}timing_i + \gamma_{12}rate_i + u_{1i} \quad (4)$$

where  $\gamma$ s are sample-level parameters and  $u_{0i}$  and  $u_{1i}$  are unexplained interindividual differences in initial level and rate of change that are assumed multivariate normal distributed with means of zero, standard deviations of  $\sigma_{u0}$  and  $\sigma_{u1}$ , and correlation  $r_{u0u1}$ . Of particular interest were the relations of EEG power development with the timing ( $\gamma_{01}$  and  $\gamma_{11}$ ) and rate ( $\gamma_{02}$  and  $\gamma_{12}$ ) of A-not-B development. Models were fit to the repeated measures data from each electrode location using the nlme package in R (Pinheiro, Bates, DebRoy, Sarkar, & Core Team, 2015) using maximum likelihood estimation, with incomplete data (5%) treated using missing at random assumptions.

## Results

Descriptive statistics for the core measures are presented in Table 1. As expected, the mean level of A-not-B performance increased with age (from  $M = 0.00$  at 6 months to  $M = 3.32$

at 12 months), with the extent of interindividual differences in performance greatest at the 9 month assessment ( $SD = 1.41$ ). In parallel, we see that average EEG power at all six electrode sites increased with age, but with no clear pattern of change in the standard deviations.

### **Interindividual Differences in Development of A-not-B Performance**

The logistic growth trajectories derived from the logistic growth models are shown in Figure 1. As can be seen, the model (red line) provided a good description of the repeated observations (black dots and lines) of performance (residual standard errors ranged from 0.73 to 9.29,  $M = 3.68$ ,  $SD = 2.04$ ), with the majority of infants first A-not-B performance at age six months being unsuccessful (score = 0), developing rapidly between age 7 and 11 months, and being able to complete the task at a 6-second delay or longer (score = 4) by age 12 months. The prototypical (average) infant obtained a score of 2 (i.e., halfway between lower and upper asymptotes) 3.68 months after the first observation (i.e.,  $6 + 3.68 = 9.68$  months), at which point infants were developing at an average instantaneous rate of 2.55 ( $SD = 3.04$ ). In other words, the prototypical infant reached a score of 2 at 9.68 months of age and at that point their rate relative to other individuals was 2.55. There were, of course, substantial individual differences both in timing and rate of development ( $SD_{\theta_2} = 2.04$ ;  $SD_r = 3.04$ ). Notably, interindividual differences in timing and rate were correlated -0.49 indicating that infants growing faster reached the point of inflection earlier. To test variability around parameter estimates, a pseudo R-squared was computed comparing the variance of all residuals to the collection of residuals from the individual models. It indicated that there was substantial variability around parameter estimates (pseudo  $R^2 = 0.842$ ).

### **Associations between development of EEG power and development of A-not-B task performance**

Interindividual differences in timing and rate of change in the development of A-not-B task performance were then examined in relation to concurrent (age 6 to 12 months) development of EEG power at the F3, F4, P3, P4, O1, O2 electrode locations using linear growth models (Equations 2 to 4). We used a stricter criterion of  $p \leq .01$  to alleviate potential concerns about the number of tests, and the results are shown in Table 2. As expected, all the models indicated that EEG power increased, on average, across the second half of the first year. For example, for F3, the prototypical infant had (ln) power of  $\gamma_{00} = 2.73$  at the first observation (age 6 months), with power increasing at  $\gamma_{10} = 0.09$  ( $SE = 0.01$ ,  $p < 0.001$ ) units per month across the seven measurements. Similarly, for O2, the prototypical infant had (ln) power of  $\gamma_{00} = 2.51$  at the first observation, with power increasing at  $\gamma_{10} = 0.07$  ( $SE = 0.01$ ,  $p < 0.001$ ) units per month across the seven measurements.

Associations between the interindividual differences in development of A-not-B performance derived from the logistic growth model (timing and rate) and the interindividual differences in the trajectories of EEG power emerged for occipital electrode locations. Neither timing nor rate of development in A-not-B performance was related to level or change in EEG power at F3, F4, P3 or P4. However, as shown in Panel E of Figure 2, individuals with faster rates of increase in A-not-B performance had lower EEG (ln) power of O1 at age 6 months,  $\gamma_{02} = -0.08$  ( $SE = .03$ ,  $p = .01$ ), and marginally greater increases in EEG power across the seven-month observation period,  $\gamma_{12} = 0.01$  ( $p = .08$ ). In parallel, and as shown in Panel F of Figure 2, individuals with faster rates of increase in A-not-B performance had lower EEG (ln) power of O2 at age 6 months,  $\gamma_{02} = -0.08$  ( $SE = .03$ ,  $p = .01$ ), and marginally greater increases in EEG (ln) power across the seven-month observation period,  $\gamma_{12} = 0.01$  ( $p = .09$ ).

### Discussion

The current study examined the timing and rate of A-not-B task performance in relation to change in EEG power across 6 to 12 months of age. This study is the first of its kind to describe the timing and rate of development of A-not-B performance using a logistic growth function and examine how differences in the behavioral development of cognitive performance are related to trajectories of brain activity.

### **Interindividual Differences in Development of A-not-B Performance**

The first aim of the study was to identify the timing and rate of A-not-B task performance change using a nonlinear growth curve model. More specifically, we examined the sigmoid-shaped logistic curve that traversed performance from an A-not-B task score of 0 to a task score of 4. As predicted, the logistic growth model provided a good depiction of repeated A-not-B performance across the latter half of the first year, capturing the observation that the majority of infants were unsuccessful at the task at 6 months, rapidly increased in performance from 7 to 11 months, and succeeded at a 6-second or greater delay by 12 months. This description is consistent with Piaget's theory of cognitive development that qualitative change may reflect the reorganization of children's thinking as they get older.

Past research has shown nonlinearities in A-not-B performance, such as a surge in skill appearing around 8 months of age (Bell & Fox, 1994), and another between 10 and 12 months (Smith & Thelen, 2003). Other work has implied a sigmoid-shaped trajectory of reaching at location *B* across age in infancy, but has not tested a nonlinear model of change (Munakata, 1998). Rather, previous research has documented nonlinearities by revealing surges in performance at various ages, while often modeling change in behavior as linear (Fischer & Rose, 1997). The current study found that A-not-B performance across 6 to 12 months of age is indeed

nonlinear, with flat lower and upper bounds at 6 and 12 months respectively, and a spike in performance between 7 and 11 months of age.

Regarding timing, infants reached the point of inflection, or a score of 2, on the A-not-B task on average at age 9.68 months. Around nine months of age may be an important time for coordinating multiple systems that are thought to be involved in the A-not-B task, such as motor control, attending to and tracking visual stimuli, inhibitory control, and working memory. Previous work has found a sharp increase in performance at 8 months of age (Bell & Fox, 1994) and that task performance at 8 months is normally distributed (Bell & Adams, 1999). In a study assessing A-not-B task performance bi-weekly in eight infants from 5 to 14 months of age (Fox et al., 1979), all 9-month-old infants were able to complete the A-not-B task at a 3-second delay. By 10 months, all infants completed the task at a 7-second delay. These findings indicate that between 9 and 10 months infants experience a rapid increase in performance on the A-not-B task, quite similar to the average age our infants reached the point of inflection. It is, however, important to note that the 7-second delay in Fox and colleagues' (1979) study is larger than the 2-second delay at the point of inflection in the current study. This difference could be due to the disparity in sample size. However, while the greatest shift in behavior occurred at around 9 months of age for both studies, this was also the age when individual differences were greatest, and many infants were tolerating delays of six seconds or greater.

The substantial interindividual differences in the timing of task proficiency gains are consistent with previous research on the A-not-B task. Diamond (1985) found large variability at 8 months of age, with some infants at this age only able to tolerate search delays of 0 seconds while other infants could tolerate 8 seconds of delay. Other work has shown individual differences a bit earlier at 7 months of age, with task completion highly dependent on the infant's

tolerance of delays (Bell & Fox, 1992). The considerable variability in this and the prior studies of infants' A-not-B performance underscores the importance of accounting for individual differences in young infants' cognitive performance. Whereas previous work has found that A-not-B performance increases monthly for at least six months (Bell & Fox, 1992; Cuevas & Bell, 2010; Diamond, 1985; Fox et al., 1979), the present study is the first to quantify those increases with respect to a logistic function that accommodates the nonlinear age-related changes in behavior across this 6- to 12-month time period. Indeed, the relative rate at the point of inflection was 2.55 on average but ranged from 0.25 to 13.04.

To date, research has not examined rates of change of A-not-B performance for individuals, thus this study is the first to identify significant individual differences in how quickly or slowly infants attain proficiency relative to their peers. Because there was variation in both timing and rate A-not-B task performance, we can assume that while the sigmoid-shaped curve describes the infants' performance gains across 6 to 12 months, the trajectories for the 28 infants are all somewhat unique (see Figure 1). Further, the negative correlation of timing and rate illustrates that earlier timing on the task is related to faster rates of acquisition, such that children who reach the halfway point in task performance at younger ages are mostly the same individuals who are making successful task gains more quickly. These findings suggest that although the latter half of the first year is a time during which there is substantial normative change, there is already substantial idiosyncrasy in how individuals are developing.

It is possible, however, that infants make the A-not-B error because they learned that the object was supposed to be hidden under A. Topál and colleagues (2008) found that the proportion of correct searches were greater in either noncommunicative or nonsocial conditions, where the experimenter was either not visible or did not face the infant. The authors proposed

that the A-not-B error may not be an indication of failing to inhibit prepotent responses or lacking a cognitive capability of some kind. Rather, the task may reflect learning information about the object's properties from the experimenter. The notion that the A-not-B task is a measure of cognitive skill is an assumption based on increasing scores of A-not-B task performance over age, but it could also be a reflection of infants' learning. Even in light of this assumption, the current study demonstrates how more sensitive analytic methods can help shed light on fundamental developmental processes of interest early in life.

### **Associations between development of EEG power and development of A-not-B task performance**

Our second aim was to examine the associations between linear change in baseline EEG power and nonlinear change in A-not-B performance. First, the results demonstrated that for all electrode sites, there was a linear increase in baseline EEG power values across 6 to 12 months of age. These findings are consistent with previous work that has described an overall linear increase in power at frontal, parietal, and occipital sites across the first year (Bell & Fox, 1992; Cuevas & Bell, 2011). The fact that the 6- to 9-Hz alpha band captured increases in power validates the existing literature that this is an appropriate frequency band for measuring brain electrical activity during infancy (Marshall et al., 2002). Previous work has suggested that increases in baseline EEG power in the infancy are indicative of emerging neural organization (Nunez, 1981). The increase in baseline power at all six electrode sites over time is suggestive of neural maturation and myelination that support the coordination of higher-order systems (Fischer & van Geert, 2014). In order to capture the functional consequences of brain activity, it is necessary to investigate how changes in baseline EEG power are related to changes in cognitive processing.

Interestingly, the current study found that rates of change for A-not-B performance were significantly associated with O1 and O2 power at age 6 months. More specifically, individuals with a faster rate of increase in A-not-B performance had lower baseline EEG power of O1 and O2 at 6 months of age, and they had larger increases in baseline power at these electrode locations across the 7-month period. Infants with higher power at the first time point (6 months of age) tended to advance on the A-not-B task more slowly over time. One potential reason for this association is that these infants were already performing the A-not-B task more successfully with longer delays and were thus ahead of infants with lower levels of initial power. Infants with lower initial levels of baseline EEG power had relatively more catching up to do, which required steeper (or faster) rates of performance over time.

Specific to occipital power, previous work has found that infants who could tolerate longer delays in A-not-B task performance also demonstrated greater baseline left hemisphere occipital power over age (Bell & Fox, 1992). Additionally, infants who did not complete the A-not-B task at 8 months had significantly lower baseline occipital power values than children who could complete the task at 0- or 2-second delays (Bell & Fox, 1997). The A-not-B task is a spatial working memory task, which requires attending to objects in space and tracking moving objects. Infants have shown an increase in general attentiveness to their environment by the end of the first year (Fox et al., 1979), which may provide further support for the relation between rapid gains of A-not-B task development and increases in baseline occipital power over time. In other words, infants' ability to advance quickly on the cognitive task may be in part linked to their increasing capability to attend to nonsocial visual events. Timing of A-not-B performance, on the other hand, was not related to initial levels or change in baseline occipital power. This

suggests that the average point of change in the curvature of the A-not-B trajectory is not dependent on levels or changes in occipital power.

Moreover, the baseline EEG assessment in the current study involved the presentation of a spinning wheel to sustain infant attention and minimize motor movement. This method suggests that EEG band power as recorded may reflect a state-dependent index of visual attention that increases over the second half of the first year. Task-related changes in alpha EEG power have been found for attention tasks in infancy (Orekhova, Stroganova, & Posikera, 2001). More recently, Xie, Mallin, and Richards (2017) demonstrated a negative relation between alpha power and infants' sustained attention. Xie et al. (2017) note that their findings contrast with the work of Bell (2001, 2002) and Orekhova and colleagues (2001) who found that increases in alpha power from baseline to task were associated with working memory and visual attention. The authors conclude that different cognitive tasks are associated with different patterns of baseline alpha EEG power changes. Broadly, this body of research suggests that the development of alpha rhythm might be linked to infants' visual attention capabilities and may depend on the cognitive task being measured.

Substantial changes in children's cognitive ability can be attributed to the coordination of multiple brain and behavior systems (Fischer & van Geert, 2014). Given the numerous requirements for successful performance on the A-not-B task, infants need to develop the systematic organization of many brain regions. It is somewhat surprising, then, that the frontal sites were not significantly associated with rates of increase in A-not-B performance for our sample, given previous literature suggesting that the prefrontal cortex plays an important role in infants' development of object permanence (Bell, 2001, 2012; Bell & Fox, 1992; Bell & Fox, 1997; Cuevas et al., 2012; Diamond & Goldman-Rakic, 1989). Occipital development may be

more robust than frontal development in the first year. Past research suggests that the occipital lobe typically develops earlier in infancy, whereas frontal development is particularly variable and develops at differing rates in the latter half of the first year (Johnson, 2001). The stability of occipital development may contribute to the significant associations between A-not-B task performance and occipital power changes. However, we are hesitant to suggest that changes in baseline occipital power are the only neural correlates of enhanced performance on the A-not-B task. Future research should replicate these analyses with a larger sample size to generalize these findings and isolate the mechanism of A-not-B performance associated with baseline occipital power.

In sum, the current findings demonstrate that increases in baseline occipital power for infants who advanced more quickly in A-not-B performance could reflect larger changes in organization and excitability of the neurons in the occipital region. Faster trajectories of A-not-B task performance (i.e., faster integration of skills such as tracking moving objects, working memory, motor response inhibition, and reaching) are thus linked to increases in occipital brain activity. The use of associations between nonlinear cognitive performance change and linear baseline EEG power change is an innovative way of examining interrelated developmental processes. However, it cannot be interpreted that increases in occipital power cause increased cognitive performance or vice versa. Additionally, it is only assumed that scalp electrodes are indicative of brain activity from specific cortical regions underlying the electrodes, and we have not directly tested whether changes in baseline EEG power are reflective of brain maturation. The notion that changes in EEG power are reflective of neural maturation is an assumption of the field, and future work is needed to specify the developmental implications of these changes. Although this work does not measure brain maturation directly or EEG power in-task,

knowledge of these patterns of brain activity in infants, in conjunction with cognitive performance, opens up the possibility to predict, and eventually understand, individual differences in executive function over time.

This study is the first of its kind to use growth curve modeling to delineate trajectories of infants' cognitive growth in relation to their brain development. Bell and Fox's (1992) study was pivotal in longitudinally assessing change in baseline EEG power over time for two groups of infants varying in A-not-B task performance, but the longitudinal sample was smaller ( $N = 13$ ), and sensitive analytic techniques could not be applied. Conversely, Cuevas and colleagues (2012) used a much larger sample ( $N = 290$ ) but fewer time points (5 and 10 months) and traditional regression analyses. The current study used nonlinear growth curves of task performance to more accurately describe the monthly change occurring for infants ( $N = 28$ ) from 6 to 12 months of age.

We utilized novel modeling techniques to capture A-not-B task performance across the second half of the first year. In this way we illustrate how contemporary analytic tools can be used to assess, and reassess, classic developmental phenomena. Using nonlinear mixed-effects models allowed us to most effectively describe trends in A-not-B development that support the discontinuities central to Piaget's theory of cognitive development, while also revealing how brain development maps onto the rates at which children advance in task attainment. Additionally, individual differences in timing and rate of A-not-B performance were shown in the sigmoid shape of the trajectories, permitting a closer and more comprehensive understanding of how variable cognitive development is in the first year. It is important to mention that the sigmoid shape of the A-not-B performance trajectory is dependent on the sampling method (Adolph, Robinson, Young, & Gill-Alvarez, 2008), and more frequent assessments within the

age window could have demonstrated linear development. However, we found that between 6 and 7 months hardly any change occurs for most infants and that between 11 and 12 months performance levels off. Without the addition of these beginning and end time points, one might assume linear increases between 6 and 7 months, as well as between 11 and 12 months.

Moreover, individuals vastly differed in their A-not-B performance (Figure 1), and the inclusion of initial emergence through to competence therefore allowed us to capture the full developmental progression for most of the infants in the study.

The current results should be viewed in the context of study limitations. Primarily, the sample was small for detecting interindividual differences in intraindividual change. More participants will be needed to generalize these findings. Second, the A-not-B task involved a well that was uncovered then recovered again once the toy was placed, rather than both wells having been covered simultaneously. The procedure we used may have primed the infant to maintain attention on the correct well (Diamond, Cruttenden, & Neiderman, 1994). Third, infant behavior was not coded during the EEG baseline session. Had there been information regarding the time the infant spent attending to the spinning wheel or amount of infant motor movement, we may have been able to more closely tie individual differences in occipital power to individual differences in visual attention. Fourth, EEG was not recorded during the A-not-B task so we could not capture any task-related variations in power. Fifth, the mathematical equation used in the analysis relied on the inflection point to measure interindividual differences at a score of 2. As this score is in the middle of the continuous scale from 0 to 4, its meaning on the scale is somewhat unclear. Moving the inflection point to different locations on the growth curve would likely reveal how rate changes across the logistic function. The selection of the score of 2 was simply to have a common point, or a parameterized feature of the trajectory, on which to

compare individuals parsimoniously using the entire measurement scale. Moreover, it was assumed that the measurement scale was linear and that cognitive development was nonlinear. An alternative approach would be to accommodate a nonlinear measurement scale and linear development. Lastly, the current study did not assess outcome behaviors beyond the age of 12 months, so the implications of these earlier, later, faster, and slower trajectories on later developmental processes and outcomes remain unknown. Future research should assess larger samples and extend measurement of these constructs beyond the age of 12 months so that we may better understand the role of early brain maturation in the long-term development of cognitive skills.

Nevertheless, this work provides evidence for the relations between brain activity and cognitive performance trajectories across the second half of the first year. By capturing the initial emergence of a skill and tracing attainment from absence through to advanced performance, this approach has the potential to not only inform our understanding of cognitive processing in infancy, but also provide theoretical and methodological foundations for future investigations of emerging developmental pathways. The contemporary analytic techniques illustrated here provide an exciting opportunity to empirically reassess our theoretical understanding of core developmental functions and processes.

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Table 1.

*Descriptive statistics for the seven monthly repeated measurements of behavior (A-not-B performance) and brain activity (EEG power).*

	Age (months)													
	6 mo		7 mo		8 mo		9 mo		10 mo		11 mo		12 mo	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
A-not-B Score	0.00	0.00	0.32	0.72	1.25	0.97	2.15	1.41	2.61	1.17	3.18	1.09	3.32	1.09
F3 Power	2.71	0.48	2.81	0.52	2.93	0.53	2.95	0.41	3.08	0.57	3.19	0.38	3.21	0.42
F4 Power	2.72	0.46	2.92	0.52	3.01	0.51	2.99	0.41	3.18	0.58	3.23	0.38	3.20	0.45
P3 Power	2.45	0.54	2.54	0.66	2.60	0.64	2.63	0.56	2.85	0.63	2.99	0.58	2.91	0.61
P4 Power	2.44	0.63	2.45	0.57	2.58	0.53	2.66	0.53	2.64	0.72	2.82	0.48	2.86	0.61
O1 Power	2.53	0.54	2.64	0.51	2.54	0.46	2.68	0.40	2.78	0.57	2.92	0.49	2.85	0.49
O2 Power	2.54	0.56	2.58	0.56	2.63	0.55	2.67	0.57	2.81	0.53	2.92	0.55	2.95	0.48

*Note.* Descriptive statistics for EEG power values are natural log transformations of power in the 6-9 Hz frequency band. Descriptive statistics are based on 195 occasions for A-not-B task performance (186 for F3, P3, O1; 185 for F4, P4; 188 for O2) nested within 28 participants. *M* = mean, *SD* = standard deviation.

Table 2.

Results from the Linear Growth Models with Logistic Model Parameters as Predictors.

	Change over Age (months)																	
	F3 Power			F4 Power			P3 Power			P4 Power			O1 Power			O2 Power		
	Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI	Est.	SE	95% CI
Fixed effects																		
Intercept, $\gamma_{00}$	2.731*	0.082	2.569, 2.893	2.796*	0.085	2.628, 2.965	2.464*	0.098	2.269, 2.658	2.440*	0.094	2.254, 2.626	2.514*	0.073	2.370, 2.659	2.509*	0.077	2.357, 2.661
Agec6, $\gamma_{01}$	0.088*	0.012	0.064, 0.112	0.082*	0.012	0.060, 0.105	0.087*	0.015	0.057, 0.117	0.070*	0.015	0.041, 0.099	0.062*	0.017	0.029, 0.094	0.072*	0.015	0.041, 0.102
Timing, $\gamma_{11}$	0.034	0.047	-0.064, 0.132	0.029	0.049	-0.072, 0.131	0.043	0.057	-0.074, 0.161	0.036	0.055	-0.076, 0.148	-0.046	0.043	-0.135, 0.042	-0.021	0.045	-0.114, 0.072
Rate, $\gamma_{12}$	-0.031	0.031	-0.095, 0.034	-0.028	0.033	-0.096, 0.039	-0.039	0.038	-0.117, 0.039	-0.052	0.036	-0.127, 0.022	-0.081*	0.029	-0.141, -0.021	-0.077*	0.030	-0.138, 0.017
Agec6 x Timing	-0.002	0.007	-0.016, 0.012	0.003	0.007	-0.011, 0.016	-0.003	0.009	-0.021, 0.015	-0.004	0.009	-0.021, 0.013	0.009	0.010	-0.010, 0.028	0.010	0.009	-0.008, 0.028
Agec6 x Rate	0.002	0.005	-0.007, 0.011	0.003	0.004	-0.006, 0.011	0.002	0.006	-0.009, 0.014	0.004	0.006	-0.007, 0.016	0.011	0.007	-0.001, 0.024	0.010	0.006	-0.002, 0.022
Random effects																		
Intercept, $\sigma_{u0}$	0.151		0.076, 0.303	0.167		0.085, 0.329	0.218		0.108, 0.440	0.185		0.089, 0.386	0.090		0.036, 0.228	0.089		0.031, 0.256
Agec6, $\sigma_{u1}$	0.001		<0.001, 0.008	0.009		<0.001, 0.009	0.003		0.001, 0.011	0.001		<0.001, 0.017	0.003		0.001, 0.012	0.001		<0.001, 0.071
Correlation, $r_{u0,u1}$	-0.008		-0.524, 0.396	-0.274		-0.654, 0.259	0.064		-0.399, 0.494	0.089		-0.539, 0.650	-0.077		-0.498, 0.384	0.416		-0.972, 0.996
Residual variance, $\sigma_e$	0.074			0.073			0.108			0.125			0.120			0.158		

Note. Unstandardized estimates and standard errors (SE) for models based on 186 occasions for F3, P3, O1, 185 for F4, P4, and 188 for O2 nested within 28 participants. \*  $p \leq .01$ .

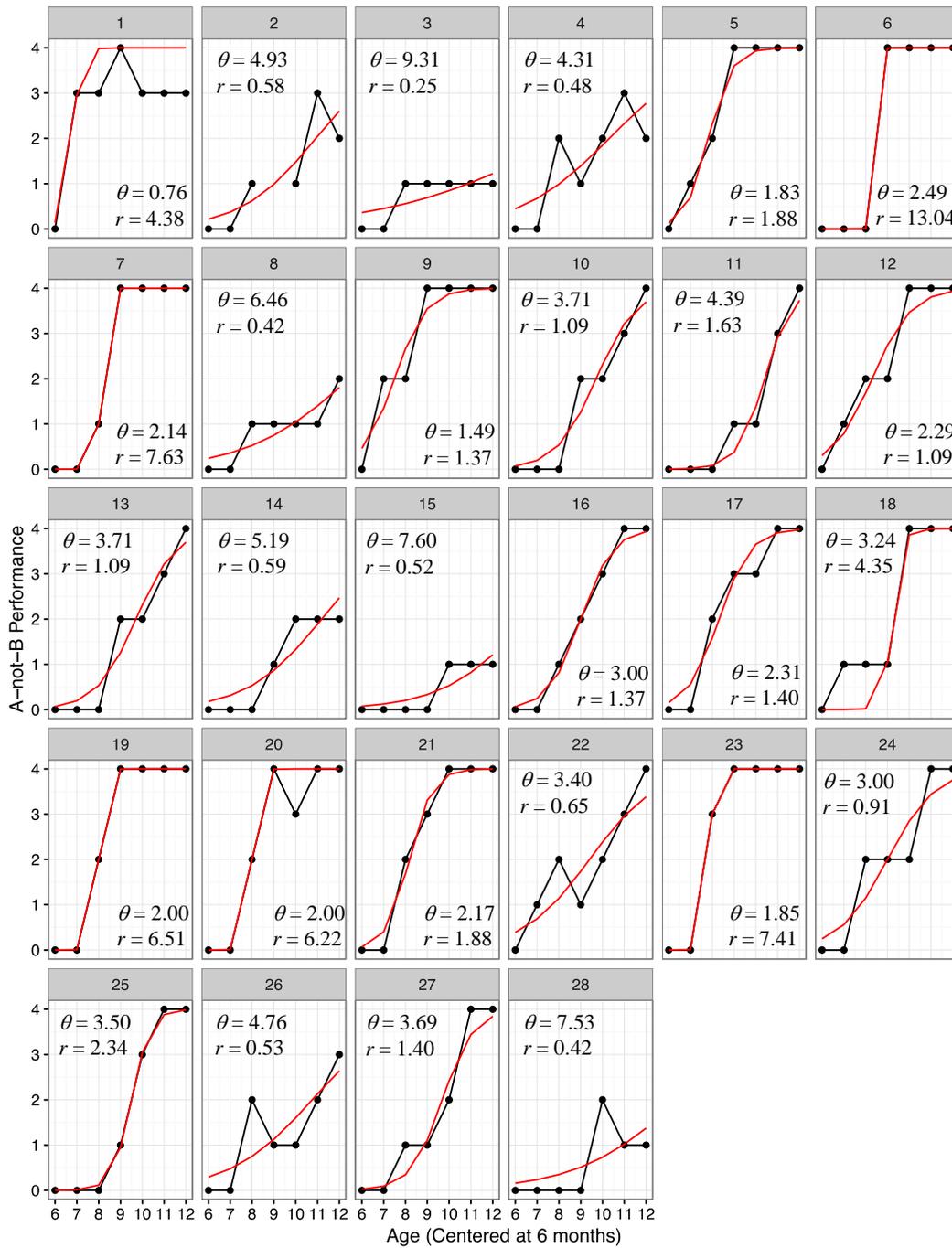
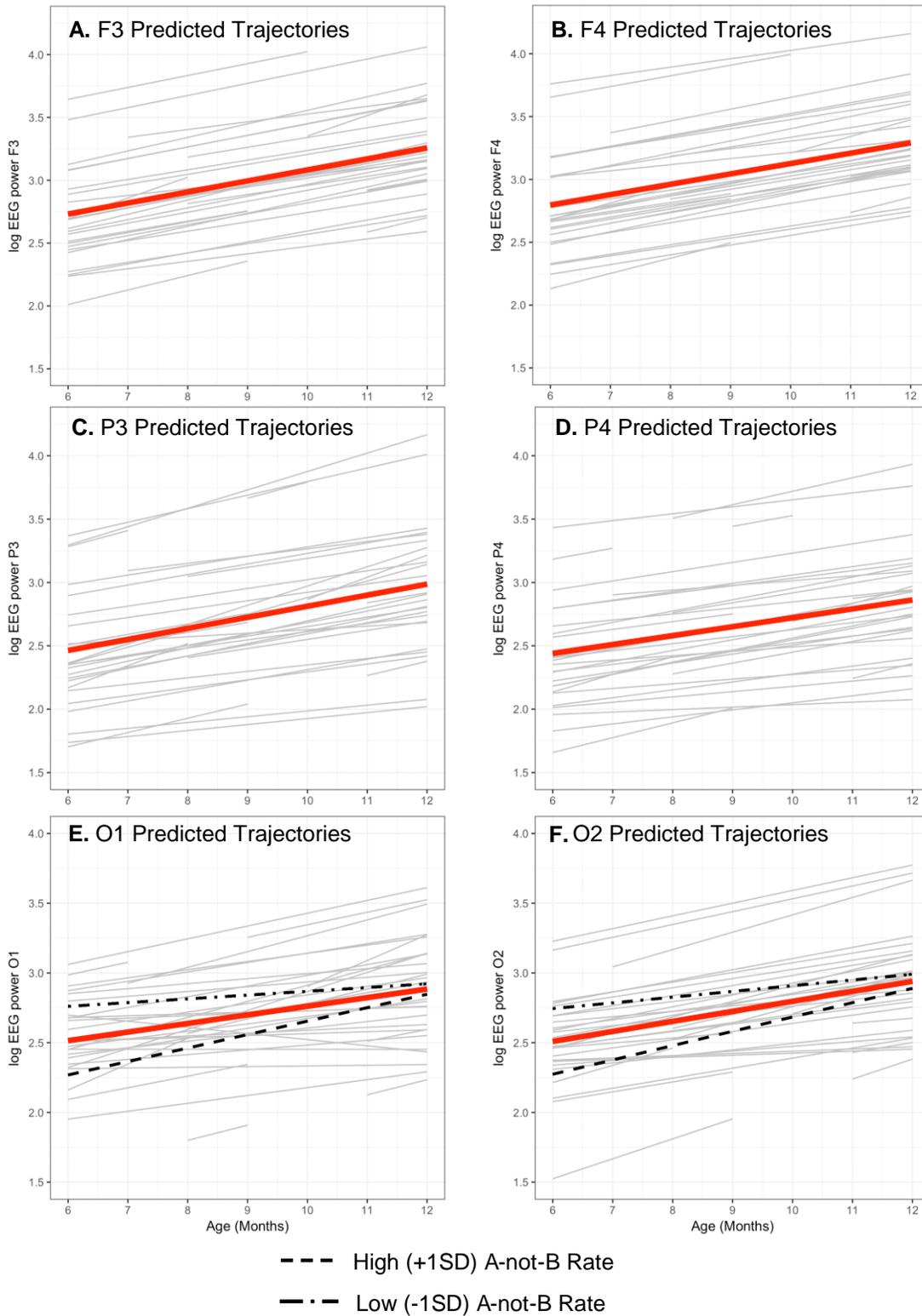


Figure 1. Predicted trajectories of nonlinear intraindividual change of A-not-B performance for  $N = 28$  children across seven assessments. Solid lines show the predicted trajectories for each individual; dotted lines show the raw data for each individual.  $\theta$  = timing of change;  $r$  = rate of change.



*Figure 2.* Predicted trajectories of linear intraindividual change of EEG power for  $N = 28$  children across seven assessments. Bolded lines show the predicted trajectories for each individual; grey lines show the raw data for each individual.