



OPEN Investigating neural correlates of attention in relation to the development of executive functions in early childhood

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Most previous studies investigating early neural predictors of Executive Function (EF) abilities focused on resting-state brain activity in infancy, with mixed findings. Here, we investigated early neural predictors of later-emerging EF abilities by measuring task-related changes in brain activity, which we argue to be more sensitive to detecting individual differences in EF skills. Sixty-six 9-month-old infants participated in an action observation and execution task, while their brain activity was recorded. Two conditions were used, which required different levels of cognitive control and social engagement: one group of infants saw an experimenter performing actions in consecutive trials and then performed similar actions themselves (the Blocked condition), while the other group performed the actions, taking turns with the experimenter (the Interleaved condition). At age five, 45 of the original infants returned for follow-up assessments and completed a battery of well-established EF tasks. Of these 45 participants, 35 infants provided usable neural data at 9 months and behavioral EF data at age 5 and were included in the final analysis. Results revealed a close link between infants' neural activity and their EF abilities that were specific to frontal theta oscillations, a neural component associated with high-order cognition, and to the Interleaved condition, which was the condition that required greater attentional control and social engagement from infants. The results highlight the importance of selecting appropriate tasks and neural measures to detect longitudinal brain-behavior relations.

Keywords Executive functions, Theta band, Alpha band, EEG, Action observation, Infancy

Executive functions (EFs) are a set of cognitive processes involved in top-down control of mental or physical actions^{1–3}. EFs begin developing in infancy and mature through adolescence^{3,4}. They have been identified as predictors of important life outcomes, including academic achievement and well-being^{5–8}. One core EF is inhibitory control, which involves using self-control to direct attention and behavior (attentional control) and overriding prepotent responses (response inhibition) to act more appropriately. Inhibitory control can manifest as resisting internal distractions, such as mind-wandering, and maintaining focus on the task at hand^{2,9}. Behavioral studies provide some evidence that cognitive abilities such as inhibition in infancy, which require attention and information processing, may predict children's later higher-order EFs^{10–13}. However, less is known about the neurobiological markers of the development and predictors of EFs.

Previous studies have identified two neurobiological markers of attention from measures of infant brain activity. These markers are event-related measures that can be captured with an electroencephalogram (EEG). The first marker is theta oscillations (4–8 Hz for adults; 3–6 Hz for infants), measured over frontal areas of the scalp. Theta oscillations have been linked to higher-order cognitive processes, such as attention allocation, information encoding, and learning (see¹⁴ for a review). For example, greater theta synchronization during the observation of items was found to be related to greater recall of the items later for both infants and adults^{15,16}. The second marker is alpha oscillations (9–12 Hz for adults; 6–9 Hz for infants), measured over occipital areas of the scalp. Alpha oscillations have been linked to perceptual processing of visual input^{17,18}. For example, greater event-related occipital alpha desynchronization is found when infants are engaged in sustained visual attention compared to total darkness¹⁹, or when they are presented with dynamic visual stimuli such as an agent performing actions^{20,21}.

Here, we investigated whether these neural correlates of attention measured in infancy correlate with the development of various EF abilities – including inhibition – later in childhood. Our approach differs from

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previous studies on the longitudinal link between brain activity and later EF in that most of them measured spontaneous brain activity during resting state, with mixed findings. For example, Kraybill and Bell found a negative relation between EEG alpha frontal power during resting and EF skills at 4 and 6 years²². In another study, Jones et al.²³ investigated the relationships between non-verbal cognitive skills and frontal power while infants watched dynamic videos of women talking and toys moving. In the study, researchers found no relations between frontal alpha power measured at 12 and 14 months and non-verbal intelligence measured at 2, 3, and 7 years—but a positive relation was found with frontal theta power²³.

While resting activity can be relevant to study brain maturation, task-related EEG may be more sensitive in detecting specific brain-behavior relations that are tightly associated with the construct of interest^{24,25}. In other words, finding a relation between a particular phenotype and brain functioning is more likely if we subject infants to conditions in which the relevant characteristics or vulnerabilities of the phenotype are most likely to emerge. In the current study, we utilized a paradigm that measured 9-month-old infant EEG in two conditions that required different levels of attentional control and social engagement. We linked event-related changes in alpha and theta oscillations longitudinally to their general EF skills at age five.

One group of infants saw an experimenter performing actions in consecutive trials and then performed similar actions themselves (Blocked condition). The other group of infants performed the actions, taking turns with the experimenter (Interleaved condition). Modern theories of attentional control suggest switching between attentional settings (e.g. the Interleaved condition) should be more mentally demanding than continuing with the same settings (e.g. the Blocked condition) due to an automatic tendency of humans to maintain attentional biases even when they are no longer relevant (see²⁶ for a review). Additionally, turn-taking creates a more socially interactive context than blocked actions, potentially enhancing infants’ engagement and sense of collaboration. The turn-taking context may place greater demands on inhibitory control, as infants must suppress their motor responses to attend to the experimenter’s actions. Thus, we expected the Interleaved condition to be more sensitive to detect longitudinal brain-behavior relations than the Blocked condition because it would more likely recruit mental processes associated with EFs (e.g., remembering who performed the last action, processing social input while simultaneously forming and inhibiting a motor plan for the next turn, among other demands).

For this study, we focused on collecting a variety of EF assessments, including those that tap into working memory and, importantly, inhibitory control. We drew on the hierarchical model of inhibitory control, which suggests that inhibitory control relies on higher-level functions (e.g., working memory) to coordinate lower-level inhibitory processes, such as attentional inhibition and response inhibition. These components are often measured based on performance in stimulus-response tasks⁹. In our study, the stimulus-response tasks we used included the Head-Shoulders-Knees-Toes task (HSKT), the Day/Night Stroop task, which both measure inhibitory control, and the Max Digit Recall stimulus-response task, which measures strictly working memory. Each stimulus-response task requires participants to selectively attend to and respond to target stimuli while simultaneously tuning out irrelevant distractions or obvious but incorrect responses that could interfere with successfully completing goal-directed actions. Lastly, we collected a parent report called the Ratings of Everyday Executive Functioning (REEF); this assessment is designed to assess the general EF abilities of children during everyday activities and distinguish between EF areas.

Methods
Participants

Data for this study were drawn from a previously conducted longitudinal study that investigated infant cognitive skills using EEG and behavioral measures. EEG data were collected from 9-month-old infants. Participants were recruited back at age 5 to collect EF data using well-established behavioral methods^{8,27–30}. For more detailed information about the experimental procedure used, see Fulcher³¹. Sixty-six nine-month-old infants (36 female, $M_{\text{age}} = 8$ months, 26 days) participated in the EEG study²⁰. Of these 66, 45 five-year-olds (25 female, $M_{\text{age}} = 5$ years 18 days) from the original cohort completed EF tasks that assessed both inhibitory control and working memory abilities. Additionally, a parent-report assessment of children’s executive functioning was collected³¹. Table 1 displays the number of participants who completed each respective EF assessment. Only participants who provided both EEG data at 9 months and EF data at age 5 were included in the analysis ($N = 35$; See Procedure below).

Procedure: 9-month-old infants

Infants’ EEG activity was recorded while they observed and executed grasping actions, as described in Meyer et al.²⁰. First, infants’ caregivers were provided a run-down of the procedure and provided written consent. Next, caregivers were directed into a testing room and asked to sit with their infant on their lap. The experimental session was recorded with three video cameras. Researchers placed a 128-sensor HydroCel Geodesic Sensor Net (Electrical Geodesics, Eugene, OR, USA) on the child’s head. While wearing the cap, infants were presented

	# Subjects
HSKT Task	38
Day/Night Stroop Task	39
Max Digit Recall	41
Ratings of Everyday Executive Functioning (REEF)	45

Table 1. Executive function assessments at five Years.



Fig. 1. Experimental setup. The infant view of the experimenter grasping a toy during an observational trial. Photos are taken from data collection by Meyer et al.²⁰.

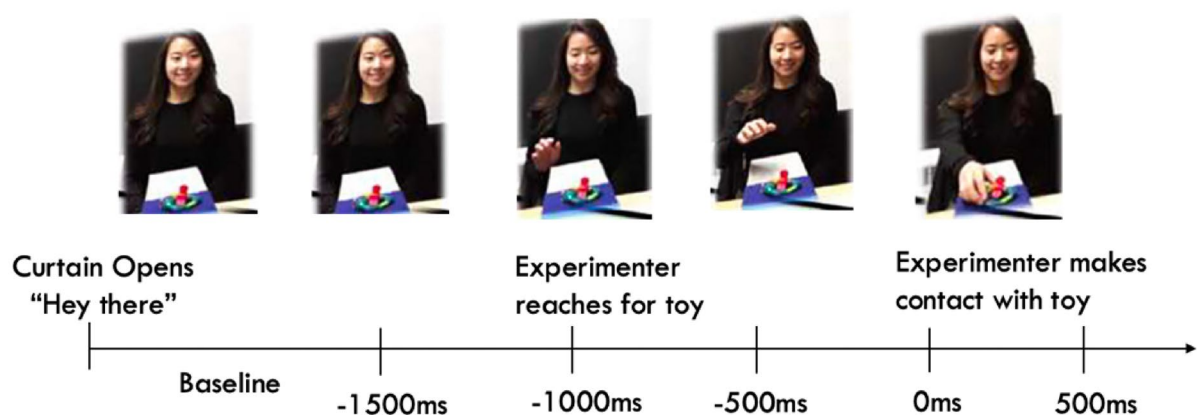


Fig. 2. Schematic timeline of an observation trial. The window of interest that we collected alpha and theta power, spans from -1500 ms until 500 ms. This power was compared to baseline, which occurred before the experimenter began reaching for the toy. Photos are taken from data collection by Meyer et al.²⁰.

with action observation trials in which they observed the experimenter reaching and grasping toys. Infants sat in front of a puppet stage on their caregiver's lap, facing one experimenter. The experimenter was hidden behind black cardboard doors that could be manually opened with a drawstring (See Fig. 1). The experiment included trials where infants observed an experimenter grasp a toy and execute grasping a toy themselves. For this experiment, we chose to focus exclusively on analyzing trials in which infants observed grasping actions to avoid electrical activity due to motor movement. Families were provided a compensation of \$20 and a t-shirt or toy for the infant.

Action observation trials

The start of observational trials began with the curtains closed. A bell rang to catch the infant's attention. Then the experimenter opened the curtain, made eye contact with and smiled at the infant (baseline window), and said: "Hey there!" Next, the experimenter proceeded to reach for and grasp a toy placed on a blue sheet. Unlike Meyer et al.²⁰ our window of interest began 1500 ms before the experimenter first made contact with the toy (i.e., -1500 ms) and ended 500 ms after the experimenter made contact with the toy (i.e., $+500$ ms) (See Fig. 2). We extended the window to begin at -1500 ms to encompass not only the period of overt movement (starting around -1000 ms) but also the earlier phase in which infants may begin to allocate attentional and cognitive resources in anticipation of upcoming action. That is, even before visible motion, contextual cues may have signaled to infants that it was the agent's turn to act, allowing for early engagement of predictive mechanisms. We expected that this window would comprise two attentional processes. On the one hand, internally controlled

focused attention (top-down) is based on predicting future events. On the other hand, externally driven attention (bottom-up) is based on the visual information from the agent's movements.

Interleaved and blocked conditions

In Meyer et al.²⁰, each infant was assigned to either a turn-taking Interleaved or a Blocked condition. The Interleaved condition began with an action observation trial (see section above), followed by one execution trial. In the execution trial, the experimenter would open the curtain and slide the blue placeholder with the toy on top close to the infant as if to offer it to the infant. Then, the infant had the choice to grab the toy. Once the infant grabbed the toy, the trial was complete, and another experimenter would approach the baby to take the toy away from them. If the infant didn't grab the toy, the experimenter would encourage them to grab the toy a few times. If the infant still refused the toy, the experimenter would bring the blue placeholder back with the toy and close the curtain. The alteration of observational and execution trials went on for a maximum of 40 trials. In this condition, infants could anticipate whether the experimenter would grasp or bring the toy closer to them based on the previous trial.

The Blocked condition was also 40 trials but involved the infant first watching the experimenter grasp 10 different toys before having the opportunity to grasp the toys 10 times in a row. These 10-trial groupings of observation vs. execution were repeated twice with 10 random toys, resulting in a total of 40 trials. Observation trials lasted about 15 s, whereas execution trials lasted until the infant successfully grasped the toy or until it was evident that the infant was no longer interested in the toy. The experiment concluded once the infant finished all 40 trials or if the infant could not complete more than two consecutive grasping or observation trials due to loss of interest.

EEG data analysis

The videos of the session were time-locked to the EEG recording using Datavyu³² and Net Station software was used to convert the EEG data into a MATLAB-compatible format (The MathWorks, Natick, MA, USA). The pre-processing followed the MADE pipeline³³ in MATLAB and involved filtering, deleting electrodes, and removing artifacts. The steps and parameters of the pre-processing were very similar to those of Meyer et al.²⁰ and closely followed the procedure outlined by Debnath et al.³⁴. The goal of the pre-processing was to remove unwanted artifacts and improve the signal-to-noise ratio while simultaneously minimizing data loss. Independent component analysis (ICA) was used to remove artifacts using the updated Adjusted Adjust to mark components with artifacts³⁵. Within our window of interest for the action observation trials, trials that included behaviors that could influence the signal, as noted by manual video coding from Meyer et al.²⁰, were removed. These behaviors included instances when the infant was performing a gross motor movement, crying, not looking directly forward, or parental interference. After these trials were excluded, we segmented the data into epochs corresponding to our predefined time windows. Each trial included a baseline window—a 500 ms segment beginning when the curtain was fully opened, and the experimenter looked and smiled at the infant—and an experimental window, which spanned from 1500 ms before the experimenter contacted the toy to 500 ms after the toy contact (see Fig. 2). For each infant, the number of baseline and experimental trials was matched. A trial was considered artifact-free only if no artifacts or interferences were present in either the experimental window or its corresponding baseline window.

To be included in the analysis, participants were required to provide data for at least two trials, following the criterion from Meyer et al.²⁰. Forty-nine nine-month-old participants met the inclusion criterion for EEG analysis. Twenty-one participants were assigned the Interleaved condition, and 28 were assigned the Blocked condition. On average, 7.6 trials (minimum trials = 2; maximum trials = 19; SD = 4.4) were usable for each participant in the action observation condition ($M_{\text{blocked}} = 7.9$, $M_{\text{interleaved}} = 7.2$). Time-frequency decomposition was computed using the EEGLAB *newtimef* function. Event-related spectral perturbation (ERSP) was calculated on the free-artifact data to estimate the baseline-corrected spectral power (in decibels) from 3 to 30 Hz for all channels and trials. Our analysis focused on alpha and theta band oscillations. Studies on EEG theta oscillatory power in early childhood suggest that the theta frequency range typically falls around 3–5 Hz in infants^{36–38} provide empirical evidence indicating that peak theta activity ranges between 3.6 and 4.8 Hz in infants aged 2 to 9 months. While there is some debate regarding the precise boundaries of theta activity, we selected the 3–5 Hz range to avoid overlap with the alpha frequency band. For alpha, studies targeting 9-month-old infants consistently focus on the 6- to 9-Hz ratio^{34,39–41}.

Power was averaged across trials in the two frequency bands of interest from the electrodes situated at frontal areas (F3 = E18, E19, E22, E23, E24, E26, E27; F4 = E2, E3, E4, E9, E10, E123, E124) and occipital areas (O1 = E66, E69, E70, E71, E74; O2 = E76, E82, E83, E84, E89) of the scalp. Since we had no predictions of whether hemisphere should influence the relation between EEG and EF, and previous studies with a similar paradigm did not find main effects or interactions of hemisphere^{20,34} we collapsed the data across the two hemispheres for each cluster of channels—but hemisphere was included in exploratory analyses. We used the resulting event-related alpha and theta power estimates to correlate to behavioral responses collected at five years.

Procedure: 5-year-old children

Of the 49 participants who provided valid EEG data, 35 were recruited at around age 5. Caregivers were sent an email with a consent form and the Rating of Everyday Executive Function (REEF) Survey, among other questionnaires, to report on their child's general EF skills. The REEF is a parent-report assessment that covers general EF abilities. It has been validated against laboratory measures of EF, such as the Digit Span and the Tower of Hanoi^{30,31}. After completing these surveys, caregivers were received a \$25 compensation. Next, the children met with an experimenter virtually over Zoom. The Zoom session included multiple games to measure the participants' EF skills: two inhibitory control tasks and one working memory task. Caregivers provided verbal

consent to keep the Zoom session recording, and then the participant engaged in tasks with the experimenter. After completing the 15-minute Zoom session, participants received another \$25 compensation.

Five-year-olds' inhibitory control and working memory tasks

Participants played three EF tasks: two of the tasks assessed inhibitory control, and one assessed working memory. The first task was the Day/Night Stroop Task, which assessed inhibitory control^{8,28}. This task involves learning a rule and inhibiting the easy (but incorrect) response when asked to apply the rule in different situations. Children were taught to say “Day” when shown an image of a night sky and to say “Night” when shown an image of a sun. Participants were given 16 trials in addition to 2 practice trials. The task was adapted for online use, where images of a night sky and the sun were displayed on a screen for 1 s, followed by two seconds of a blank screen between trials. The second inhibitory control task (Head-Shoulders-Knees-Toes (HSKT)) was a game similar to Simon Says, where children were asked to do the opposite of what they were told (i.e., if they were told to touch their head, they should touch their toes)²⁷. First, children were only told to touch their heads and toes and respond in the opposite. Children completed four training trials and were given direct feedback. Then, 10 test trials were administered. If children correctly responded to a majority of the first 10 trials, an additional rule was introduced. Children were then taught to touch their knees when instructed to touch their shoulders. So, they needed to remember how to respond when told to touch their head, shoulders, knees and toes. The third EF task (Max Digit Recall) was a forward digit span task which assessed working memory. Children were told strings of numbers of increasing length (beginning with 2-digit strings) and asked to repeat the numbers they heard²⁹. Children were first introduced to a stuffed animal that repeated a two-digit string of numbers after the experimenter. Children were then asked if they could be like the stuffed animal and copy the experimenter. After two practice trials of two-digit number strings, the experimenter added more numbers to the string. This continued until children incompletely repeated two number strings in a row.

Videos of these sessions were coded. For the Day/Night Stroop Task, participants were given a score of 1 for correctly saying the opposite word to the picture shown (e.g., saying “day” when shown the night sky), 0.5 for saying the word that matches a picture, but then self-correcting to the correct response, or 0 for saying the word that matches the picture (e.g., saying “day” when shown the image of a sun). The proportion of correct responses (“day” for night images and “night” for day images) was calculated from these scores. For the Head-Shoulders-Knees-Toes, preschoolers were given a score of 2 for correctly touching the opposite body part that was said (e.g., touching their head if the experimenter said touch your toes), a 0 if their response matched the prompt (e.g., touching their head when told to touch their head) or a 1 if they made the motion towards the incorrect response, but then self-correcting to the opposite motion of the prompt. Again, these numbers together created a score of the proportion of trials in which preschoolers provided the correct response. Both the Day/Night Stroop and the HSKT involve inhibiting the prepotent response and remembering rules. In the Max Digit Span task, participants heard two different strings of numbers of the same length before moving on to a string with one additional digit. After incorrectly recalling two strings of numbers in a row, the task was concluded. The maximum number of digits recalled correctly was recorded as children's working memory score. Finally, the parent-reported REEF survey included items that captured different components of EF: inhibitory control (e.g., “Waits for you to finish on the phone before seeking your attention”), working memory (e.g., “Fetches all items requested by adult [e.g., Does not forget what he/she was asked to get]”), cognitive flexibility (e.g., “Rephrases language when another person doesn't understand what he/she is saying”), emotion regulation (e.g., “Recovers quickly from a disappointment or change in plans [e.g., the family is no longer going out for dinner]”), and planning (e.g., “Plans ahead when playing games [e.g., what he/she should do on the next turn]”). For more detailed information about the REEF survey, see Nilsen et al.³⁰, and for detailed information about any of the behavioral tasks, see Fulcher³¹.

Analysis plan

This study drew on previously existing data to examine the link between neural measures of attention in infancy (9 months) and EF assessments at age 5. First, we ran correlations between the scores of the HSKT Task, the Day/Night Stroop Task, the Max Digit Recall, and the REEF to create a General 5-year-old EF score. To control for multiple comparisons, we used the Bonferroni correction. Where certain assessments were not correlated with each other, we excluded those measures from the final EF general scores (details in the *Results* section). Next, we assessed whether children showed general differences in EF general scores based on condition, using a between-subjects ANOVA with condition (Blocked vs. Interleaved) as a factor and EF score as the dependent variable. A similar analysis of ANOVA was then conducted to investigate whether infants showed differences in their neural correlates depending on the condition, with the number of trials as a covariate.

Finally, we investigated relations between neural correlates of attention (frontal theta ERS and occipital alpha ERD) and EF. Power across the alpha and theta bands were computed from the time window of interest (1500 ms before the experimenter first made contact with the toy (i.e., −1500 ms) until 500 ms after the experimenter made contact with the toy (i.e., +500) (See Fig. 2). Our linear regression model tested for longitudinal relations between occipital alpha power recorded on the scalp and EF at age 5 (specifically the General 5-year-old EF z-score) and relationships between frontal theta power recorded on the scalp and EF at age 5. The main analyses focused on frontal theta and occipital alpha, as these components have been previously linked to attentional processes. However, to better understand the specificity of any significant effect, we also tested the same models with frontal alpha as a control for frontal theta and occipital theta as a control for frontal alpha.

Table 2 displays the number of subjects who had usable EEG alpha and theta power at 9 months and came back for testing at age 5. We performed a linear regression model using the lme4 package⁴². The dependent variable in the linear regression model was the General EF z-score at age 5 and the fixed effects included EEG power (either alpha or theta), Condition (Interleaved vs. Blocked), and the interaction between EEG power and

	9-month EEG Power (Blocked)	9-month EEG Power (Interleaved)	Total # Subjects
General 5-year-olds' EF z-score	18	17	35
Rating of Everyday EF (REEF)	17	17	34

Table 2. Number of participant for Correlations.

	HSKT Task	Day/Night Stroop Task	Max digit recall	REEF
HSKT Task	1	-	-	-
Day/Night Stroop Task	0.516 (<0.001)*	1	-	-
Max Digit Recall	-0.111 (0.746)	0.225 (0.084)†	1	-
REEF	0.408 (0.006)*	0.424 (0.004)*	0.090 (0.710)	1

Table 3. Correlation table of executive function assessments at age 5.

Condition (Interleaved vs. Blocked). The model also included the number of artifact-free EEG trials to control for possible spurious effects. When the interaction between EEG power and condition was significant, a follow-up analysis was conducted, separating participants by condition. Additionally, exploratory analysis investigated the effects of hemisphere, time window (anticipation or observation), and brain-behavior correlations in the central electrodes, as these electrodes are typically related to motor activity, which is recruited when observing others' actions. These factors were added to the original model (e.g., EF ~ EEG score * Condition * Hemisphere + #trials), and the results were analyzed separately for each exploratory question. Bonferroni correction was used in each level of analysis to control for multiple comparisons.

Sample size and statistical power

To estimate the statistical power of detecting brain-behavior correlations under different conditions, we conducted a simulation-based power analysis using the structure and parameter estimates of our fitted linear model. Across 1,000 simulated datasets with the same sample size ($N=35$), the interaction between Theta and Condition reached statistical significance ($\alpha=0.05$) in 73% of simulations. While slightly below the conventional 80% threshold, this level of power still reflects a moderate-to-high likelihood of detecting the effect given the observed parameters. Importantly, this study is based on a longitudinal design with infants, which presents substantial logistical and methodological challenges that often limit achievable sample sizes.

Results

Correlations between EF measures at age 5

Some individual scores that preschoolers received on the EF tasks at age 5 were positively correlated with each other and remained significant after correcting for multiple comparisons ($N=6$), with an adjusted $p=0.008$. Specifically, preschool-aged children who performed better on the HSKT task also performed better on the Day/Night Stroop Task ($r(37)=0.516, p<0.001$; Table 3). These are two tasks that measure inhibitory control. However, the Max Digit Recall (a measure of working memory only) was not correlated to the proportion correct on the HSKT task ($r(38)=-0.111, p=0.746$) and the Day/Night Stroop Task ($r(39)=0.225, p=0.084$; Table 3). The parent report of children's EF had a significant positive correlation with the HSKT task ($r(37)=0.408, p=0.006$) and the Day/Night Stroop Task ($r(38)=0.424, p=0.004$) but not with the Max Digit Recall ($r(40)=-0.090, p=0.710$; Table 3). For simplicity, we excluded non-correlating factors from further analysis. The remaining correlated measures—all except the Max Digit—were combined into a single General 5-year-old EF score.

Differences within each age group based on condition

There were no significant differences in children's general executive function (EF) scores between conditions (Blocked vs. Interleaved), $F(1, 33)=0.19, p=0.67, \eta^2=0.006$, indicating that the groups were well matched in EF abilities. Similarly, no significant effects of condition were observed in frontal Theta activity, $F(1, 33)=3.81, p=0.059, p_{\text{bonf}}=0.119, \eta^2=0.10$, or occipital Alpha activity, $F(1, 33)=4.92, p=0.033, p_{\text{bonf}}=0.067, \eta^2=0.13$, though the latter approached significance. Infants in the Interleaved condition showed marginally greater alpha suppression relative to baseline (see Fig. 3). Given that Meyer et al.²⁰ reported a significant effect of condition in central alpha (mu rhythm), a confirmatory analysis was conducted on central electrodes. This analysis revealed a significant condition effect, $F(1, 33)=5.46, p=0.024, p_{\text{bonf}}=0.048, \eta^2=0.15$, with greater mu desynchronization in the Interleaved compared to the Blocked condition. These findings align with Meyer et al.²⁰ despite analyzing a smaller sample size (infants who provided EF data) and using extended trial durations to capture both action anticipation and observation.

Neural correlates of attention and EF at age 5

Frontal theta ERS and EF at age 5

The linear model with the General 5-year-old EF z-score as the dependent variable and 9-month frontal theta power during action encoding as the independent variable revealed a significant interaction between EF and condition ($p=0.004; p_{\text{bonf}}=0.008$). Follow-up analysis investigated the relations between EF and EEG, separating

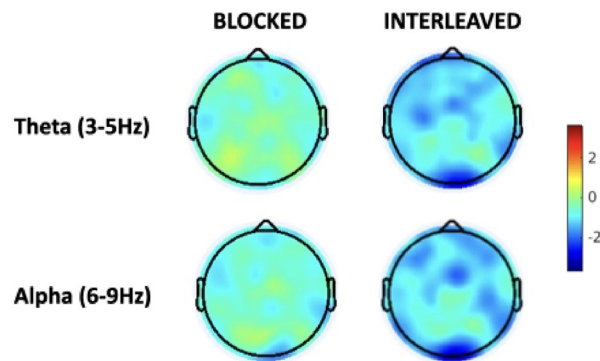


Fig. 3. Topographic distribution of baseline-corrected theta power (3–5 Hz; top panel) and alpha power (6–9 Hz; bottom panel) separated by condition: Blocked condition on the left column and Interleaved condition on the right column. For the contrast, cooler colors represent less relative power (i.e., desynchronization), and warmer colors represent more power relative to the baseline (i.e., synchronization) (For interpretation of the reference to color in this figure legend, the reader is referred to the Web version of this article).

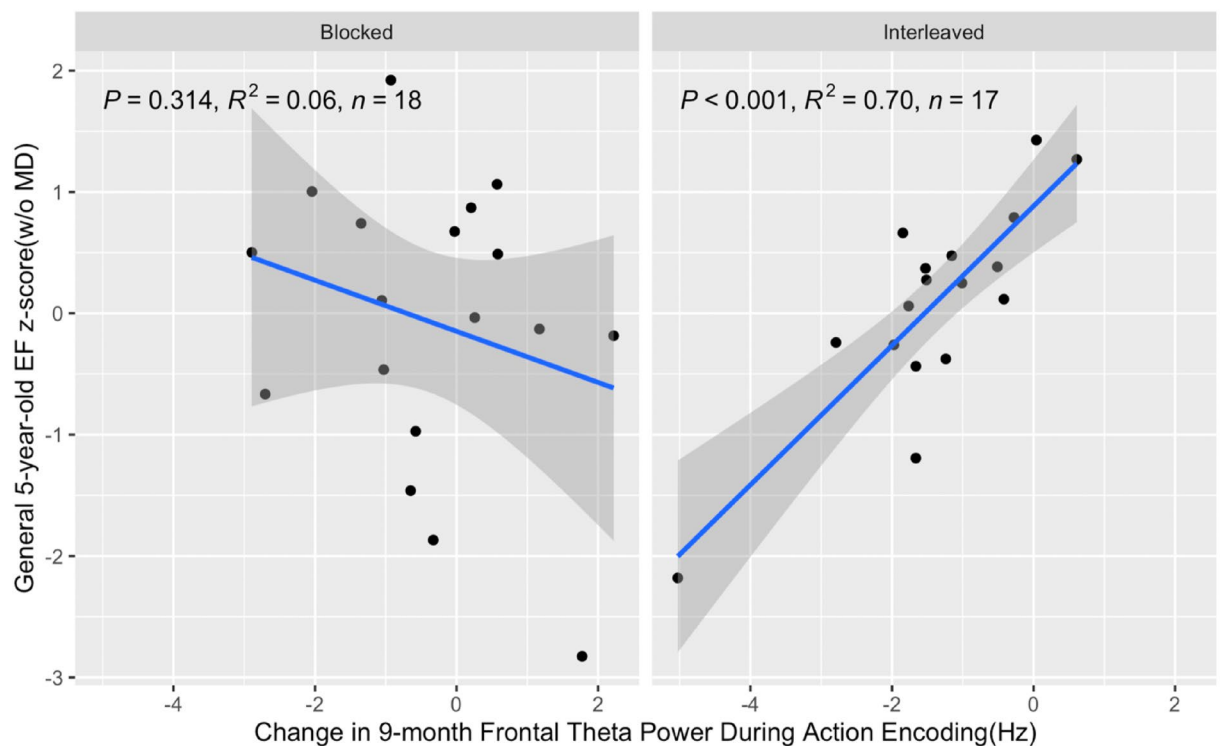


Fig. 4. Correlations of General 5-year-old EF score as a function of Event-Related infant theta power recorded while observing an experimenter grasp a toy. The two graphs are split by the condition infants were assigned to—either the Blocked or Interleaved condition. The p-value, R^2 , and number of subjects (n) are displayed on the graph. Power greater than zero indicates event-related theta synchronization (ERS) or an increase in power relative to baseline. Whereas power less than zero indicates event-related theta desynchronization or a decrease in power relative to baseline. EF z-scores greater than zero indicate better performance on EF tasks and vice-versa for values less than zero. The linear regression line is in blue, with the standard deviations shaded in grey. 9-month infants assigned to the Interleaved condition with theta ERD performed better on EF assessments at 5 years old.

participants by condition. In the Blocked condition, the model found no significant relation ($R^2(15)=0.04$, $p=0.323$, $p_{\text{bonf}}=0.64$; see Fig. 4). However, in the Interleaved condition, frontal event-related theta power was positively related to the General 5-year-old EF score ($R^2(14)=0.66$, $p<0.001$, $p_{\text{bonf}}<0.001$; see Fig. 4). To check for the effect of potential outliers, the analysis was performed again after excluding one participant from the

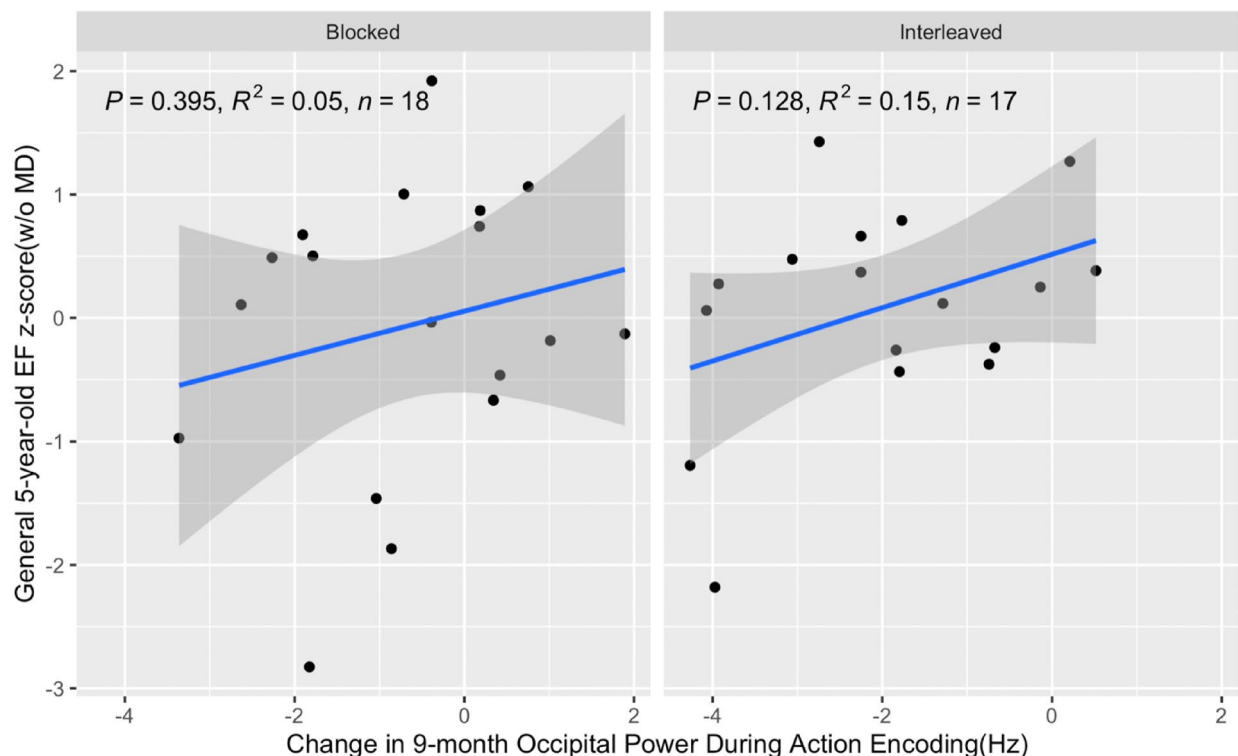


Fig. 5. Correlations between General 5-year-old EF score and infant alpha power recorded while paying attention to and observing an experimenter grasp a toy. The two graphs are split by which condition infants were assigned to—either the Blocked condition or the Interleaved condition. The p-value, R^2 , and number of subjects (n) are displayed on the graph. Power greater than zero indicates event-related alpha synchronization (ERS) or an increase in power relative to baseline. Whereas power less than zero indicates event-related alpha desynchronization or a decrease in power relative to baseline. EF z-scores greater than zero indicate better performance on EF tasks and vice-versa for values less than zero. The linear regression line is in blue, with the standard deviations shaded in grey. There is no significant relationship between alpha ERD and EF assessments at 5 years old. **Central Alpha.** Given that the task used in this study has been shown to elicit central alpha suppression (mu rhythm), an exploratory analysis examined the relationship between mu rhythm and executive function (EF) scores. Although mu rhythm is not a direct measure of attention, it may reflect motor system engagement during action observation, which could be linked to later EF development. In fact, prior research has suggested associations between action planning and the development of EF^{43–49}. While the current task primarily targets action prediction and understanding, these processes are likely related, as suggested by the links found between infants' motor skills and their neural synchronization during the anticipation of others' actions⁵⁰. However, the analysis revealed no significant associations or interactions between mu power and EF scores (all $p > 0.10$).

Interleaved condition with extreme theta values (value $< \text{mean} - 2.5 \text{ SD}$). Despite the strength of the correlation between frontal theta and EF scores decreased, it remained significant ($R^2(13) = 0.38$, $p = 0.0247$, $p_{\text{bonf}} = 0.049$).

When the same analysis was conducted with frontal alpha as control, the model found no significant effects or interactions (all $p > 0.1$). Finally, exploratory analyses included hemisphere (left; right) and time window (action anticipation: -1500 to -500 ms; action observation: -500 ms to 500 ms) in the original model. No significant effects or interactions were found for the exploratory factors (all $p > 0.1$).

The results reveal that infants with greater frontal theta power from baseline during action observation at 9 months had higher EF scores at age 5. This effect was specific to the theta band—no results were found for frontal alpha—and it supports our hypothesis that frontal theta (a marker of learning and attention) is positively related to later EF.

Alpha ERD and EF at age 5

Occipital Alpha The linear model with General 5-year-old EF z-score as the dependent variable and change in 9-month occipital alpha power during action encoding as the independent variable revealed no main effects ($p = 0.327$, $p_{\text{bonf}} = 0.654$) or interactions with condition ($p = 0.857$, $p_{\text{bonf}} = 1$; see Fig. 5). When the same analysis was conducted with occipital theta as control, no main effects or interactions were found either (all $p > 0.1$). Additionally, exploratory analyses with hemisphere or time window found no significant effects or interactions related to the exploratory factors (all $p > 0.1$).

Discussion

In this study, we used existing infant EEG data to uncover early neural markers of later EF development. Our findings suggest that, under the right task conditions, 9-month-old infants' event-related frontal theta power can predict later EFs measured at age 5. However, infant event-related occipital alpha power does not correlate with general EF skills during childhood. Importantly, EF in this study was assessed through tasks requiring inhibitory control and working memory, as well as a parent-report measure of children's general, everyday EF abilities. The Max Digit Recall task, a pure working memory measure, was excluded due to a lack of correlation with other EF tasks. Although EF is often conceptualized as comprising interrelated components, even in early childhood^{1,51}, empirical findings during the toddler and preschool years frequently show no significant association between working memory and inhibitory control tasks^{45,49}. The current results are consistent with these empirical findings.

As hypothesized, the positive correlation between event-related theta power and later EF was limited to the Interleaved condition—no correlation was found in the Blocked condition. We argue that switching turns in the Interleaved condition may require more voluntary inhibitory control on the part of the infant, as each observation trial requires inhibiting the attentional settings from the previous trial. In the Blocked condition, infants may have attended to the trials in a kind of “autopilot” mode, with minimal cognitive engagement. EF is typically recruited when individuals cannot rely on automatic responses²; thus, EF-related abilities may become more utilized in the Interleaved condition.

An alternative, non-exclusive interpretation is that the Interleaved condition, more so than the Blocked condition, places greater demands on inhibitory control mechanisms to support adherence to a specific social rule—in this case, taking turns to act on toys. Similarly, the Day/Night Stroop and the HSKT tasks require the use of inhibitory control to follow the rules of a game embedded in a social context between the experimenter and the participant. As argued by Doebel³, executive functions are always engaged in the service of particular goals, which are influenced by mental content, including knowledge, beliefs, and norms. Longitudinal studies that similarly tap into tasks requiring control in service of specific goals may be better positioned to capture individual differences.

Related to the previous point, prior studies have suggested that there's a link between EF development and early action processes that are involved in goal-directed control^{43–49}. However, the present study found that motor-related brain activity (mu rhythm) during the observation of others' actions was not predictive of later EF development. This may be because the current design focuses on action understanding and prediction rather than action planning. In such a task, neural mechanisms related to attention and information encoding seem to be better predictors of later EF skills.

Despite both theta ERS and alpha ERD being linked to attention, only theta ERS correlated with later EFs. This result is not surprising, given that theta ERS has been suggested to index high-order cognitive processes, such as attention control, information encoding, and readiness to learn^{15,16,52,53}. However, alpha ERD is more related to perceptual processing, such as visual attention^{17–19}. Additionally, theta oscillations recorded from sensors overlying frontal areas of the scalp have been associated with mPFC-related activities involved in cognitive control and focused attention^{54,55}. Individual differences in infant scalp-recorded frontal theta may be an index of variability in the functional maturation of the prefrontal cortex (PFC). This would be consistent with theoretical views that link the maturation of the PFC during the last half of the first year of life with the emergence of higher-order cognitive processes^{56,57}.

Due to limitations in spatial resolution, it remains unclear which brain areas specifically contributed to power changes in scalp EEG. Theta band power changes may serve different cognitive functions in different brain areas⁵⁸, and thus, other methods should be used to better elucidate the brain areas that contributed to the current findings. Additionally, theta oscillations have been proposed to mediate brain inter-regional communication^{59–61}. For example, it has been suggested that an increase in theta synchronization mediates the coordination of memory-related brain networks during encoding and retrieval of information⁶². Similarly, theta phase coherence has been found to coordinate neural circuits involved in executive functions by synchronizing the medial prefrontal cortex with other task-related cortical regions⁶³. Future studies could investigate the relation between functional networks and the emergence of EFs, rather than focusing on EEG power changes on specific scalp locations (see Colomer et al.⁵⁰, for an example of a link between functional networks and behavioral skills in infancy).

Another limitation is that the number of artifact-free trials was relatively low for some participants, increasing the noise-to-signal ratio. This limitation is common in infant action observation studies^{20,34,41}, primarily due to the stringent data cleaning required to exclude movement artifacts, interference, inattention, and other noise. Although the current analysis controlled for the potential effects of trial count variability, a higher number of usable trials would be preferable to capture better individual differences that may be obscured by measurement noise.

Finally, future research should replicate this experiment with a larger sample size to confirm the replicability of the findings and reduce the influence of individual data points. For example, despite the main correlation between frontal Theta and EF remaining significant when removing one data point, the effect size was reduced considerably. Note that despite 66 participants participating in the EEG study, the relation between EEG and later EF was analyzed with a sample of only 35 participants. This decrease in sample size is not surprising given the difficulty of collecting EEG data in infancy and the large time gap between the first assessment at nine months and the subsequent assessment at five years. However, given that only the Interleaved condition was sensitive enough to detect individual differences in brain responses that predicted later EFs, future studies could focus directly on the Interleaved condition or a similar cognitive demanding task to investigate longitudinal brain-behavior relations.

In conclusion, the current study provides preliminary evidence that task-related brain activity in infancy can predict EF skills in childhood. The findings highlight the importance of selecting a task that can more likely elicit individual differences in the phenotype of interest. Finally, the results extend previous findings on the relation between theta power and EFs by showing brain-behavior links beyond cross-sectional designs.

Data availability

The dataset analyzed in the current study are available from the corresponding author on reasonable request.

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References

1. Diamond, A. Executive functions. *Annu. Rev. Psychol.* **64**, 135–168. <https://doi.org/10.1146/annurev-psych-113011-143750> (2013).
2. Diamond, A. Executive functions. *Handb. Clin. Neurol.* **173**, 225–240. <https://doi.org/10.1016/B978-0-444-64150-2.00020-4> (2020).
3. Doebel, S. Rethinking executive function and its development. *Perspect. Psychol. Sci.* **15**, 942–956. <https://doi.org/10.1177/1745691620904771> (2020).
4. Broomell, A. P. R. & Bell, M. A. Longitudinal development of executive function from infancy to late childhood. *Cogn. Dev.* **63**, 101229. <https://doi.org/10.1016/j.cogdev.2022.101229> (2022).
5. Gathercole, S. E., Pickering, S. J., Knight, C. & Stegmann, Z. Working memory skills and educational attainment: evidence from National curriculum assessments at 7 and 14 years of age. *Appl. Cogn. Psychol.* **18**, 1–16. <https://doi.org/10.1002/acp.934> (2004).
6. Moffitt, T. E. et al. A gradient of childhood self-control predicts health, wealth, and public safety. *Proc. Natl. Acad. Sci. U S A.* **108**, 2693–2698. <https://doi.org/10.1073/pnas.1010076108> (2011).
7. Zelazo, P. D. & Carlson, S. M. The neurodevelopment of executive function skills: implications for academic achievement gaps. *Psychol. Neurosci.* **13**, 273–298. <https://doi.org/10.1037/pne0000208> (2020).
8. Gerstadt, C. L., Hong, Y. J. & Diamond, A. The relationship between cognition and action: performance of children 3½–7 years old on a Stroop-like day-night test. *Cognition* **53**, 129–153. [https://doi.org/10.1016/0010-0277\(94\)90068-X](https://doi.org/10.1016/0010-0277(94)90068-X) (1994).
9. Tiego, J., Testa, R., Bellgrove, M. A., Pantelis, C. & Whittle, S. A hierarchical model of inhibitory control. *Front. Psychol.* **9**, 1339. <https://doi.org/10.3389/fpsyg.2018.01339> (2018).
10. Johansson, M., Marciszko, C., Brocki, K. & Bohlin, G. Individual differences in early executive functions: A longitudinal study from 12 to 36 months. *Infant Child. Dev.* **25**, 533–549. <https://doi.org/10.1002/icd.1952> (2016).
11. Cuevas, K. & Bell, M. A. Infant attention and early childhood executive function. *Child. Dev.* **85**, 397–404. <https://doi.org/10.1111/cdev.12126> (2014).
12. Devine, R. T., Ribner, A. & Hughes, C. Measuring and predicting individual differences in executive functions at 14 months: A longitudinal study. *Child. Dev.* **90**, e618–e636. <https://doi.org/10.1111/cdev.13217> (2019).
13. Kraybill, J. H., Kim-Spoon, J. & Bell, M. A. *Infant attention and age 3 executive function*. [Unpublished manuscript] (2019).
14. Begus, K. & Bonawitz, E. *The rhythm of learning: Theta oscillations as an index of active learning in infancy*. [Unpublished manuscript] (2020).
15. Klimesch, W. EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Res. Rev.* **29**, 169–195. [https://doi.org/10.1016/S0165-0173\(98\)00056-3](https://doi.org/10.1016/S0165-0173(98)00056-3) (1999).
16. Begus, K., Southgate, V. & Gliga, T. Neural mechanisms of infant learning: differences in frontal theta activity during object exploration modulate subsequent object recognition. *Biol. Lett.* **11**, 20150041. <https://doi.org/10.1098/rsbl.2015.0041> (2015).
17. Ergenoglu, T. et al. Alpha rhythm of the EEG modulates visual detection performance in humans. *Cogn. Brain Res.* **20**, 376–383. <https://doi.org/10.1016/j.cogbrainres.2004.03.009> (2004).
18. Thut, G., Nietzel, A., Brandt, S. A. & Pascual-Leone, A. α -band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *J. Neurosci.* **26**, 9494–9502. <https://doi.org/10.1523/JNEUROSCI.0875-06.2006> (2006).
19. Stroganova, T. A., Orekhova, E. V. & Posikera, I. N. *EEG alpha rhythm in infants*. [Unpublished manuscript] (1999).
20. Meyer, M., Chung, H., Debnath, R., Fox, N. A. & Woodward, A. L. Social context shapes neural processing of others' actions in 9-month-old infants. *J. Exp. Child. Psychol.* **213**, 105260. <https://doi.org/10.1016/j.jecp.2021.105260> (2022).
21. Yoo, K. H., Cannon, E. N., Thorpe, S. G. & Fox, N. A. Desynchronization in EEG during perception of means-end actions and relations with infants' grasping skill. *Br. J. Dev. Psychol.* **34**, 24–37. <https://doi.org/10.1111/bjdp.12115> (2016).
22. Kraybill, J. H. & Bell, M. A. Infancy predictors of preschool and post-kindergarten executive function. *Dev. Psychobiol.* **55**, 530–538. <https://doi.org/10.1002/dev.21057> (2013).
23. Jones, E. J. H. et al. Infant EEG theta modulation predicts childhood intelligence. *Sci. Rep.* **10**, 17680. <https://doi.org/10.1038/s41598-020-67687-y> (2020).
24. Finn, E. S. *Is it time to put rest to rest?* [Unpublished manuscript] (2021).
25. Rosenberg, M. D. & Finn, E. S. *How to establish robust brain-behavior relationships without thousands of individuals*. [Unpublished manuscript] (2022).
26. Awh, E., Belopolsky, A. V. & Theeuwes, J. Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends Cogn. Sci.* **16**, 437–443. <https://doi.org/10.1016/j.tics.2012.06.010> (2012).
27. Cameron Ponitz, C. E. et al. Touch your toes! Developing a direct measure of behavioral regulation in early childhood. *Early Child. Res. Q.* **23**, 141–158. <https://doi.org/10.1016/j.ecresq.2007.01.004> (2008).
28. Carlson, S. M. Developmentally sensitive measures of executive function in preschool children. *Dev. Neuropsychol.* **28**, 595–616. https://doi.org/10.1207/s15326942dn2802_3 (2005).
29. Grégoire, J. & Van der Linden, M. Effect of age on forward and backward digit spans. *Aging Neuropsychol. Cogn.* **4**, 140–149. <https://doi.org/10.1080/13825589708256642> (1997).
30. Nilsen, E. S., Huyder, V., McAuley, T. & Liebermann, D. Ratings of everyday executive functioning (REF): A parent-report measure of preschoolers' executive functioning skills. *Psychol. Assess.* **29**, 1–10. <https://doi.org/10.1037/pas0000308> (2017).
31. Fulcher, M. T. *The development of help-seeking as a problem-solving tool* (Doctoral dissertation). University of Chicago. (2023). <https://doi.org/10.6082/uchicago.7542>
32. Datavyu Team. *Datavyu: A Video Coding Tool* (Datavyu Project, 2014).
33. Debnath, R. et al. The Maryland analysis of developmental EEG (MADE) pipeline. *Psychophysiology* **57** (e13580). <https://doi.org/10.1111/psyp.13580> (2020).
34. Debnath, R., Salo, V. C., Buzzell, G. A., Yoo, K. H. & Fox, N. A. Mu rhythm desynchronization is specific to action execution and observation: evidence from time-frequency and connectivity analysis. *Neuroimage* **184**, 496–507. <https://doi.org/10.1016/j.neuroimage.2018.09.053> (2019).
35. Leach, S. C. et al. Adjusting ADJUST: optimizing the ADJUST algorithm for pediatric data using geodesic Nets. *Psychophysiology* **57**, e13566. <https://doi.org/10.1111/psyp.13566> (2020).

36. Orekhova, E. V., Stroganova, T. A., Posikera, I. N. & Elam, M. EEG theta rhythm in infants and preschool children. *Clin. Neurophysiol.* **117**, 1047–1062. <https://doi.org/10.1016/j.clinph.2005.12.027> (2006).
37. Tan, E. et al. Theta activity and cognitive functioning: integrating evidence from resting-state and task-related developmental electroencephalography (EEG) research. *Dev. Cogn. Neurosci.* **67**, 101404. <https://doi.org/10.1016/j.dcn.2024.101404> (2024).
38. Michel, C. et al. Theta- and alpha-band EEG activity in response to eye gaze cues in early infancy. *Neuroimage* **118**, 576–583. <https://doi.org/10.1016/j.neuroimage.2015.06.042> (2015).
39. Broomell, A. P. R., Savla, J. & Bell, M. A. *Infant electroencephalogram coherence and toddler inhibition are associated with social responsiveness at age 4. Infancy* **24**, 43–56 (2019). <https://doi.org/10.1111/inf.12273>
40. Goldman, I. R., Stern, M. J., Engel, J. Jr. & Cohen, S. M. Simultaneous EEG and fMRI of the alpha rhythm. *Neuroreport* **13**, 2487–2492. <https://doi.org/10.1097/01.wnr.0000047685.08940.d0> (2002).
41. Chung, H., Meyer, M., Debnath, R., Fox, N. A. & Woodward, A. Neural correlates of familiar and unfamiliar action in infancy. *J. Exp. Child. Psychol.* **220**, 105415. <https://doi.org/10.1016/j.jecp.2022.105415> (2022).
42. Bates, D., Mächler, M., Bolker, B. M. & Walker, S. C. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* **67**, 1–48. <https://doi.org/10.18637/jss.v067.i01> (2015).
43. Yanaoka, K. & Saito, S. Repeated sequential action by young children: developmental changes in representational flexibility of task context. *Dev. Psychol.* **55**, 780–792. <https://doi.org/10.1037/dev0000678> (2019).
44. Yanaoka, K. & Saito, S. Contribution of executive functions to learning sequential actions in young children. *Child. Dev.* **92**, e1–e17. <https://doi.org/10.1111/cdev.13489> (2021).
45. Gottwald, J. M., Achermann, S., Marciszko, C., Lindskog, M. & Gredebäck, G. An embodied account of early executive-function development. *Psychol. Sci.* **27**, 1600–1610. <https://doi.org/10.1177/0956797616667447> (2016).
46. Pennequin, V., Sorel, O. & Fontaine, R. Motor planning between 4 and 7 years of age: changes linked to executive functions. *Brain Cogn.* **74**, 107–111. <https://doi.org/10.1016/j.bandc.2010.07.003> (2010).
47. Schröer, L., Cooper, R. P. & Mareschal, D. Left, right, left, right: 24–36-month-olds' planning and execution of simple alternating actions. *Infancy* **27**, 1104–1115. <https://doi.org/10.1111/inf.12494> (2022).
48. Schröer, L., Cooper, R. P. & Mareschal, D. Science with duplo: multilevel goal management in preschoolers' toy house constructions. *J. Exp. Child. Psychol.* **206**, 105067. <https://doi.org/10.1016/j.jecp.2020.105067> (2021).
49. Schröer, L., Cooper, R. P. & Mareschal, D. Assessing executive functions in free-roaming 2- to 3-year-olds. *Front. Psychol.* **14** (1210109). <https://doi.org/10.3389/fpsyg.2023.1210109> (2023).
50. Colomer, M. et al. Action experience in infancy predicts visual-motor functional connectivity during action anticipation. *Dev. Sci.* **26**, e13339. <https://doi.org/10.1111/desc.13339> (2023).
51. Miyake, A. et al. The unity and diversity of executive functions and their contributions to complex frontal lobe tasks: A latent variable analysis. *Cogn. Psychol.* **41**, 49–100. <https://doi.org/10.1006/cogp.1999.0734> (2000).
52. Orekhova, E. V., Stroganova, T. A. & Posikera, I. N. Theta synchronization during sustained anticipatory attention in infants over the second half of the first year of life. *Int. J. Psychophysiol.* **32**, 151–172. [https://doi.org/10.1016/S0167-8760\(99\)00011-2](https://doi.org/10.1016/S0167-8760(99)00011-2) (1999).
53. Xie, W., Mallin, B. M. & Richards, J. E. Development of infant sustained attention and its relation to EEG oscillations: an EEG and cortical source analysis study. *Dev. Sci.* **21**, e12562. <https://doi.org/10.1111/desc.12562> (2018).
54. Cavanagh, J. F. & Frank, M. J. Frontal theta as a mechanism for cognitive control. *Trends Cogn. Sci.* **18**, 414–421. <https://doi.org/10.1016/j.tics.2014.04.012> (2014).
55. Ishii, R. et al. Medial prefrontal cortex generates frontal midline theta rhythm. *Neuroreport* **10**, 675–679. <https://doi.org/10.1097/00001756-199903220-00020> (1999).
56. Colombo, J. & Cheatham, C. L. The emergence and basis of endogenous attention in infancy and early childhood. *Adv. Child. Dev. Behav.* **34**, 283–322. [https://doi.org/10.1016/S0065-2407\(06\)80010-8](https://doi.org/10.1016/S0065-2407(06)80010-8) (2006).
57. Diamond, A. *Normal Development of Prefrontal Cortex from Birth To Young Adulthood: Cognitive Functions, Anatomy, and Biochemistry* (Oxford University Press, 2002).
58. Brzezicka, A. et al. Working memory load-related theta power decreases in dorsolateral prefrontal cortex predict individual differences in performance. *J. Cogn. Neurosci.* **31**, 1290–1307. https://doi.org/10.1162/jocn_a_01417 (2018).
59. Gruber, M. J. et al. Theta phase synchronization between the human hippocampus and prefrontal cortex increases during encoding of unexpected information: A case study. *J. Cogn. Neurosci.* **30**, 1646–1656. https://doi.org/10.1162/jocn_a_01302 (2018).
60. Benchenane, K. et al. Coherent theta oscillations and reorganization of spike timing in the hippocampal-prefrontal network upon learning. *Neuron* **66**, 921–936. <https://doi.org/10.1016/j.neuron.2010.05.013> (2010).
61. Mizuhara, H., Wang, L. Q., Kobayashi, K. & Yamaguchi, Y. A long-range cortical network emerging with theta Oscillation in a mental task. *Neuroreport* **15**, 1233–1238. <https://doi.org/10.1097/01.wnr.0000126755.09715.b3> (2004).
62. Solomon, E. A. et al. Widespread theta synchrony and high-frequency desynchronization underlies enhanced cognition. *Nat. Commun.* **8**, 1704. <https://doi.org/10.1038/s41467-017-01763-2> (2017).
63. Mizuhara, H. & Yamaguchi, Y. Human cortical circuits for central executive function emerge by theta phase synchronization. *Neuroimage* **36**, 232–244. <https://doi.org/10.1016/j.neuroimage.2007.02.026> (2007).

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Author contributions

A.T., M.C., and T.F. designed the research. A.T., T.F., and H.C. performed the research. A.T., and M.C. analyzed the data and wrote the paper. T.F. analyzed the data and edited the paper. H.C. and A.W. contributed unpublished reagents/analytic tools and edited the paper.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

The University of Chicago's Social and Behavioral Sciences Institutional Review Board approved all study

procedures (IRB #H10193), and methods were performed in accordance with the relevant guidelines and regulations. Written informed consent was obtained from the children's legal guardian(s) before participating in each task.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-13713-w>.

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