Infant EEG microstate dynamics relate to fine-grained patterns of infant attention during naturalistic play with caregivers

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Abstract

As infants grow, they develop greater attentional control during interactions with others, shifting from patterns of attention primarily driven by caregivers (exogenous) to those that are more self-directed (endogenous). The ability to endogenously control attention during infancy is thought to reflect ongoing brain development and is influenced by patterns of joint attention between infant and caregiver. However, whether measures of infant attentional control and caregiver behavior during infant-caregiver interactions relate to patterns of infant brain activity is unknown and key for informing developmental models of attentional control. Using data from 43 infant-caregiver dyads, we quantified patterns of visual attention with dyadic, head-mounted eye tracking during infant-caregiver play and associated them with the duration of infant EEG microstate D/4 measured during rest. Importantly, microstate D/4 is a scalp potential topography thought to reflect the organization and function of attention-related brain networks. We found that microstate D/4 associated positively with infant-led joint attention rate but did not associate with caregiver-led joint attention rate, suggesting that supporting infants' initiatives in joint attention during play may be critical for the neurobiological development of attentional control. Further, we found that microstate D/4 associated negatively with infant attention shifts rate and positively with infant sustained attention duration, suggesting that increased stability of microstate D/4 may reflect maturation of attentional control and its underlying neural substrates. Together, our findings provide novel insights into how infant attentional control abilities and infant-caregiver visual behavior during play are associated with the spatial and temporal dynamics of infant brain activity.

Significance Statement

The ability to control attention endogenously during infancy has been associated with individual differences in future language skills and executive and self-regulatory functions. However, how the infant brain supports the development of attentional control is unknown. Using dyadic, head-mounted eye tracking during infant-caregiver play with toys and microstate analysis of infant EEG during resting state, we found associations between measures of attentional control and brain activity underlying attention-related brain networks. Our findings suggest that EEG microstates have the potential to identify infants at increased risk for altered developmental outcomes and aid in assessing the impact of early interventions. Further, they underscore the significance of sensitive and supportive infant-caregiver interactions and inform early prevention and intervention strategies.

Main Text

Introduction

Infants learn about the visual world by orienting and attending to the salient characteristics of their immediate, physical environment. Their caregivers encourage learning by creating sensitive and supportive interactions during play, which set the stage for the early development of attentional control. Attentional control is the ability to engage and disengage attention endogenously, or voluntarily, and flexibly (1, 2). During infancy, caregivers provide attentional control, for example, by presenting novel toys during play, which attract attention and also aid in soothing (3). However, infants slowly learn to exert control over their own attention, and their rudimentary ability to do this during the first year of postnatal life has been associated with individual differences in future language skills (4) and executive and self-regulatory functions (5–7). Recent advancements in eye tracking technology – namely, the use of dyadic, head-mounted eye tracking (D-ET) in naturalistic contexts (8, 9) – have begun to clarify which specific features of infant-caregiver play facilitate the development of attentional control. However, how the infant brain supports – and/or is supported by – this unfolding developmental process is largely unknown.

One marker of increasingly endogenous control over attention during infancy is the development of sustained, focused attention (10). When infants encounter a novel stimulus, they orient their attention to it, and they look at it for some period of time. The duration of looking at objects grows from infancy through early childhood, and children become better at resisting peripheral distractions (10). This is thought to reflect the maturation of attention-related brain networks including the frontoparietal (orienting) and cingulo-opercular (executive) networks that support how children respond to stimuli in the environment and learn to control their own emotions and cognitions (10, 11). Moreover, caregivers and infants collaboratively shape interactions during play that support the development of sustained attention. For example, joint attention, or when caregivers and infants coordinate their own visual attention with that of their partner to share a common point of reference (12), has been shown to increase the duration of infant sustained attention to objects during play (13), even after caregivers have looked away (14). Bouts of joint attention can be led either by infants (i.e., infant looks at object first and caregiver follows) or caregivers (i.e., caregiver looks at object first and infant follows). Both influence the infant's ability to sustain attention in real-time; though, prior work has demonstrated bouts of infant-led joint attention to be more common during play (13).

The neural correlates of sustained and joint attention have been previously studied using electroencephalography (EEG), which offers a direct, noninvasive, and low-cost measure of brain function and organization that can be collected from infants during various states of arousal or activity. Historically, researchers have assessed local (i.e., region of interest) event-related potential (ERP) or frequency-based (i.e., power) EEG measures during periods of sustained (15–19) or joint attention (see review by Bradley et al. (20)) while infants watched stimuli (e.g., objects, faces) on a screen. More recently, Xie et al. (21) showed changes associated with global (i.e., network-based) EEG functional connectivity (i.e., weighted phase lag index and graph theory measures) that differed during compared to in the absence of sustained attention. Together, these studies have suggested that periods of sustained and joint attention are accompanied by intrinsically maintained tonic alertness, improved information processing efficiency, and distinct patterns of functional connectivity (7, 8). While these studies have been very informative for understanding how the brain supports or responds to bouts of infant sustained and joint attention, the included experimental tasks do not accurately capture how patterns of visual attention unfold in the rich and complex dyadic interactions that infants are exposed to every day. In an effort to study the development of attention in a more naturalistic context, Phillips et al. (23) recorded EEG during infant-caregiver play, and videos of each partner's face, and found that endogenous oscillatory activity (i.e., theta power) did not increase before bouts of infant-led joint attention, but that infants showed neural activity associated with anticipatory processing (i.e., increased alpha suppression) when caregivers joined their attention. They suggested that their results

demonstrate that infants perceive – at the neural level – when their caregivers respond to their initiations (23). This work strongly indicates that examining the relationship between measures of attention during infant-caregiver play and infant brain function and organization is likely to enhance understanding of how both caregiver behavior and the infant brain support the development of attentional control in the context of everyday interactions.

To date, no studies have examined the relationship between temporally and spatially fine-grained D-ET measures of attention during infant-caregiver play and reliable network-based EEG measures of intrinsic functional brain organization measured separately. Understanding whether increasingly endogenous control over attention during infancy is associated with changes in intrinsic brain activity thought to support the maturation of attention-related brain networks is a critical first step for investigating how changes in patterns of infant brain activity are shaped by – and/or shape – infant-caregiver interactions over development. In addition, given the challenges of collecting task-based EEG from infants and concerns about the reliability of EEG task data at this age, establishing the presence (or absence) of associations between infant attention and patterns of infant functional brain organization that can be reliably measured is key for developing biomarker(s) that may potentially identify infants at heightened risk for altered developmental outcomes and aid in assessing the impact of early interventions. One promising and reliable network-based method for characterizing brain function and organization using EEG during infancy is microstate analysis. Microstates are patterns of scalp potential topographies that reflect very short periods (i.e., typically less than ~150 ms) of synchronized neural activity (i.e., large-scale functional networks) evolving dynamically over time (24, 25). A small number of four to seven canonical microstates, each with a distinct spatial topography, have been replicated and consistently shown to explain the majority of topographic variance in the EEG signal recorded in the absence of external task demands (i.e., resting state, passive video-watching) in infants (26), children (27–29), and adults (see review by Michel & Koenig, (25)). Their temporal properties – global explained variance (GEV), duration, coverage, and occurrence (see Michel & Koenig, (25) for overview) – have been previously reported to be highly reliable even with small amounts of data (26, 30–34) and show unique variation in how their values associate with individual differences in behavior. Critically, canonical microstate D/4, which shows a fronto-central topography, is thought to, in part, represent attention network function and organization. Specifically, source localization and simultaneous EEG-functional magnetic resonance imaging (fMRI) studies have reported areas that overlap with the frontoparietal network in both children and adults (29, 35–37). Recent work has also shown that the temporal properties of microstate D/4 associated with task-evoked, error-related activity in 4-8-year-old children (29). Source localization further indicated that their neural sources overlapped with the frontoparietal network, suggesting that microstate D/4 supports higher-order cognitive processes involved in error processing, including both top-down, goal-directed (i.e., dorsal attention network) and bottom-up, stimulus-driven (i.e., ventral attention network) control of attention (29, 38). Accordingly, microstate D/4 may similarly provide an objective measure of attention network function and organization during infancy and inspire work to better understand the potentially bidirectional and causal pathways between infant-caregiver interactions and the development of attentional control during infancy.

The current, cross-sectional study investigated whether microstate D/4 (referred to as microstate 4 hereafter) duration (i.e., the average time that microstate 4 was present before transitioning to another microstate) during passive video-watching would associate with D-ET measures of attentional control as reported in prior work (i.e., infant-led and caregiver-led joint attention, the rate of infant attention shifts, and the average duration of infant sustained attention) during infant-caregiver free play with novel toys. Our sample included 43, 5-10-month-old infants and their caregivers. We predicted that microstate 4 duration would associate with the rate of infant-led, but not caregiver-led joint attention, and the average duration of infant sustained attention. We also predicted that microstate 4 duration would associate with the rate of infant attention shifts, but in the opposite direction of the associations with joint and sustained attention. However, we did not make specific predictions about the directionality of each relationship (i.e., positive or negative) and considered all analyses to be exploratory.

Results

Microstate Analysis. Five microstates were identified for the group of 43 infants (Fig. 1). Microstate 4 showed a fronto-central spatial topography, and its mean duration was approximately normally distributed (mean = 83.63; standard deviation = 6.44; range = 72.61-96.69; Fig. 1). Descriptive statistics for the other four microstates are available in *SI Appendix, Table S1*. The Spearman-Brown split-half reliability coefficient for the duration of microstate 4 was .86 (see *SI Appendix* for additional details), indicating excellent internal consistency as previously demonstrated in Bagdasarov et al. (26).

Descriptive Statistics for D-ET Variables.

Infant-led and caregiver-led joint attention rate. A paired samples *t*-test revealed that bouts of infant-led joint attention to toys (mean = 6.16 bouts per minute; standard deviation = 2.58; range = 1.16-12.64) occurred at a significantly higher rate than bouts of caregiver-led joint attention to toys (mean = 1.59 bouts per minute; standard deviation = 1.01; range = 0-3.91), $t(42) = 11.77$, $p < .001$ (Fig. 2A). Both the rate of infant-led and caregiver-led joint attention followed an approximately normal distribution, but the rate of infant-led joint attention showed much more variability across dyads.

Infant attention shifts rate. The mean rate of infant attention shifts was 30.54 times per minute (standard deviation = 9.46; range = 14.48-71.63), which is similar to what has been previously reported in the literature (14). The mean rate of infant attention shifts followed an approximately normal distribution, except there was one outlier (i.e., one infant had a rate of 71.73 attention shifts per minute; Fig. 2B). When this outlier was removed, the mean rate of infant attention shifts was 29.57 (standard deviation = 7.04; range = 14.48-47.61).

Infant sustained attention duration. As observed in previous work (14), most infant looks to toys were brief in duration (mean = 2.38 seconds; standard deviation = 0.79; range = 1.13-4.47; Fig. 2C). Of all looks, 22.23% met the threshold for sustained attention. The mean duration of bouts of infant sustained attention followed an approximately normal distribution and as expected its mean across infants (mean = 6.15 seconds; standard deviation = 1.28; range = 3.99-9.79; Fig. 2D) exceeded the mean of the overall distribution of looks.

Hierarchical Regression Analyses. All models included age and time of EEG data collection in the first step. The second step included one of the four D-ET variables: infant-led joint attention rate (model 1), caregiver-led joint attention rate (model 2), infant attention shifts rate (model 3), or infant sustained attention duration (model 4). For each model, regression tables with additional details are available in *SI Appendix, Tables S2-S5*. Multivariate outliers were found in the data for models 2 ($n = 4$), 3 ($n = 2$), and 4 ($n = 2$), and they were removed before performing each regression. See *SI Appendix, Tables S6-S8* for models when these outliers were not removed.

Model 1. In step one, age and time of EEG data collection explained a significant proportion of the observed variation in microstate 4 duration, $F(2, 40) = 6.07$, adjusted $R^2 = .19$, $p = .005$. In step two, the addition of infant-led joint attention rate was associated with a statistically significant increment to the proportion of the observed variation explained in microstate 4 duration, Δ adjusted $R^2 = .08$, $F(1, 39) = 5.08$, $p = .030$. The final model containing all three predictors explained a significant proportion of the observed variation in microstate 4 duration, $F(3, 39) = 6.15$, adjusted $R^2 = .27$, Bonferroni-corrected $p = .006$. Results indicated that a one standard deviation increase in infant-led joint attention rate associated with a .31 standard deviation increase in microstate 4 duration, all else held constant, $t(39) = 2.25$, $p = .030$ (Fig. 3A).

Model 2. In step one, age and time of EEG data collection explained a significant proportion of the observed variation in microstate 4 duration, $F(2, 36) = 4.55$, adjusted $R^2 = .16$, $p = .017$. In step two, the addition of caregiver-led joint attention rate was not associated with a statistically significant increment to the proportion of the observed variation explained in microstate 4 duration, Δ adjusted $R^2 = .00$, $F(1, 35) = 0.99$, $p = .33$. The final model containing all three predictors did not explain a significant proportion of the observed variation in microstate 4 duration, $F(3, 35) = 3.36$, adjusted $R^2 = .16$, Bonferroni-corrected $p = .118$.

Model 3. In step one, age and time of EEG data collection explained a significant proportion of the observed variation in microstate 4 duration, $F(2, 38) = 6.81$, adjusted $R^2 = .23$, $p = .003$. In step two, the addition of infant attention shifts rate was associated with a statistically significant increment to the proportion of the observed variation explained in microstate 4 duration, Δ adjusted $R^2 = .11$, $F(1, 37) = 7.64$, $p = .009$. The final model containing all three predictors explained a significant proportion of the observed variation in microstate 4 duration, $F(3, 37) = 7.88$, adjusted $R^2 = .34$, Bonferroni-corrected $p = .001$. Results indicated that a one standard deviation increase in infant attention shifts rate associated with a .36 standard deviation decrease in microstate 4 duration, all else held constant, $t(37) = -2.76$, $p = .009$ (Fig. 3B).

Model 4. In step one, age and time of EEG data collection explained a significant proportion of the observed variation in microstate 4 duration, $F(2, 38) = 6.81$, adjusted $R^2 = .23$, $p = .003$. In step two, the addition of infant sustained attention duration was associated with a statistically significant increment to the proportion of the observed variation explained in microstate 4 duration, Δ adjusted $R^2 = .08$, $F(1, 37) = 5.75$, $p = .022$. The final model containing all three predictors explained a significant proportion of the observed variation in microstate 4 duration, $F(3, 37) = 7.02$, adjusted $R^2 = .31$, Bonferroni-corrected $p = .003$. Results indicated that a one standard deviation increase in infant sustained attention duration associated with a .32 standard deviation increase in microstate 4 duration, all else held constant, $t(37) = 2.40$, $p = .022$ (Fig. 3C).

Discussion

We examined whether fine-grained D-ET measures of infant and caregiver attention during naturalistic infant-caregiver play related to the duration of infant EEG microstate 4 during resting state. We found that an increased rate of infant-led joint attention associated with an increased duration of microstate 4. However, there was no relationship between the rate of caregiver-led joint attention and the duration of microstate 4. Also, we found that an increased rate of infant attention shifts associated with a decreased duration of microstate 4. Lastly, an increased duration of infant sustained attention associated with an increased duration of microstate 4. Therefore, as we predicted, the activity of microstate 4 related to the rate of infant-led joint attention and the duration of infant sustained attention, and in the opposite direction (positive) of its predicted relationship with the rate of infant attention shifts (negative).

Our findings indicate that the frequency of infant led joint attention bouts varies substantially across infants and is associated with individual neurobiological differences measured at rest using EEG. Specifically, we showed that the rate of infant-led joint attention bouts related to the duration of microstate 4 while caregiver-led ones did not. This may suggest that when infants are given space to drive their own attention toward an object, and that of their caregiver's (i.e., a goal-directed behavior), they support the maturation of their own attention-related brain networks (i.e., infant self-organizes (39)). Interestingly, prior work has reported a positive correlation between the duration of infant-caregiver joint attention to an object and infant sustained to the same object after joint attention has ended (14). As a result, an alternative, though not mutually exclusive interpretation is that caregivers support the development of attention related brain networks by creating a context that minimizes distractions and supports continued visual processing of salient objects (i.e., caregiver scaffolding (40)). Nevertheless, the current results indicate that sensitive and supportive caregiving in the context of play (i.e., allowing infants to lead interactions and responding appropriately) plays a critical role in shaping the maturation of brain networks associated with developing attentional control (41).

Longer periods of sustained attention during play are an important marker of increasingly endogenous control over attention during infancy. Given this, the positive association between the durations of sustained attention and microstate 4 in the current study suggest that larger values of microstate 4 duration may reflect the maturation of attention-related brain networks known to support the development of attentional control (i.e., frontoparietal/orienting, cingulo-opercular/executive). Importantly, as infants' abilities in sustaining attention grow, they spend less time shifting their attention between objects, and they become better at resisting distractions from stimuli in the environment. As a result, our finding that higher rates of infant attention shifts were associated with decreased duration of microstate 4 further supports the suggestion that larger values of microstate 4 duration reflect the maturation of attention-related brain networks. In fact, prior work has demonstrated that more efficient orienting (i.e., less frequent and unnecessary shifts of attention) associated with increased activity of the executive network (42, 43). Thus, increased duration of microstate 4 may similarly reflect increased activity of the executive network during infancy. Further, this suggestion is in line with prior studies in adults showing increased temporal properties of microstate 4 during tasks requiring increased attentional demands (35, 44–46).

The current study provides several novel insights for understanding how changes in patterns of infant brain activity are shaped by – and/or shape – infant-caregiver interactions over development. First, our findings suggest that attentional control during infancy is associated with the activity of microstate 4. Therefore, microstate 4 may serve as a neurobiological marker for the early development of attentional control during infancy and, in line with this, may be longitudinally predictive of language, executive, and self-regulatory abilities during early childhood. If true, this would be a significant step toward identifying infants at risk for poor attentional control outcomes using an objective and reliable measure of brain activity. However, assessment of the utility of microstate 4 during infancy in predicting cognitive and behavioral outcomes during early childhood is now needed and will require large samples to assess this longitudinal possibility. Fortunately, multiple large-scale, longitudinal infant EEG studies such as HEALthy Brain and

Child Development Study (47), Bucharest Early Intervention Project (48), Bangladesh Early Adversity Neuroimaging Study (49), Safe Passage Study (50), YOUth Cohort Study (51), Eurosibs Consortium (52), and Baby Siblings Research Consortium (53) are now underway and will provide important opportunities for doing this type of work and the development of novel analytical approaches in support of it (e.g., machine learning).

Second, our findings are in line with prior work suggesting that caregivers scaffold the development of attentional control by allowing infants to lead play interactions and following their lead, and additionally show that this pattern of interaction during play associates with the activity of microstate 4. If infant-caregiver interactions shape the activity of microstate 4, and/or vice versa, then altered infant-caregiver interactions may disrupt the developmentally expected transition from exogenous to endogenous attention. For example, a recent review and meta-analytic study found that infants born prematurely demonstrated a short-term advantage in visual-following during the neonatal period, but heightened risk for visual attention impairments cascading from more reflexive, exogenous (i.e., visual-following) to more complex, endogenous functions (i.e., visual recognition memory, sustained attention) during the first two years of postnatal life (54). As a result of these difficulties with visual attention in prematurely born infants, caregivers may subsequently change the way they interact with their infants (e.g., increased directedness or intrusiveness or less engagement during play) and, unintentionally, disrupt the natural development of attentional control. Altered infant-caregiver interactions may also negatively affect the subsequent development of skills dependent on these dyadic interactions, including language, executive, and self-regulatory functions (10, 55). Toward this end, future research should build on our work to develop a mechanistic understanding of how infant-caregiver interactions and the activity of microstate 4 influence the development of attentional control in infants at risk for poor outcomes, such as premature infants.

Strengths and limitations. This is the first study to investigate the relationship between the temporal properties of EEG microstates and eye tracking measures of visual attention during infant-caregiver play, furthering our developmental understanding of the associations between infant-caregiver interactions, infant attention, and brain activity. Critically, although our study is a step toward measuring real-world infant behaviors and relating it to brain activity, infant-caregiver interactions during four minutes of play are unlikely to fully represent how infants and caregivers interact at home in their everyday environment. That is, we only captured a small snapshot of infant-caregiver behavior. Still, these simple interactions have been shown to have an enormous impact on learning over time (56). For example, joint attention is incrementally refined over time through experience over the course of early development (14, 57, 58). Further, we did not quantify other sensory and motor behaviors known to contribute to episodes of joint and sustained attention. Yet, prior work has shown that caregivers engage in different types of behaviors within joint attention beyond coordination of their eye gaze including talk and touch to support infant sustained attention (13, 59, 60). It may be important for future work to quantify all of these caregiver behaviors to build a more comprehensive understanding of how caregivers support infants' initiatives in joint attention and relate to their brain activity. However, given the time-consuming nature of coding D-ET data (i.e., it took our D-ET coders eight hours on average to code just the eye gaze of each dyads' data), novel innovations in automated video-coding approaches (61, 62) are critical for this and now needed.

Conclusion

In conclusion, our findings indicate that features of infant attention during play are uniquely associated with specific spatial and temporal dynamics of electrical brain activity. These findings also further underscore how caregivers play a crucial role in fostering the development of attentional control and associated brain activity by encouraging play scenarios where infants can actively explore their environment and lead interactions. Critically, this work employed a highly reliable approach for measuring infant brain activity (i.e., microstate analysis) and eye tracking measures that reflect attention in real-world contexts. As a result, and in consideration of future research, the current study highlights the potential for developing EEG microstate 4 as a biomarker for identifying infants at risk for altered attention-related developmental outcomes and measuring the potential neurobiological effects of early prevention and intervention strategies for mitigating them.

Materials and Methods

Participants. Infant-caregiver dyads were part of a larger study investigating the impact of bias and discrimination on prenatal and postnatal maternal health and infant development. All caregivers identified as female. Study details including recruitment and eligibility are available in Bagdasarov et al. (26). Sixty-five infant-caregiver dyads participated in one or two lab visits when infants were approximately 5-7-months and/or 8-10-months of age. Of these, 43 infant-caregiver dyads met the following inclusion criteria for the current study: (a) infants were required to have at least four minutes of preprocessed EEG data as recommended by previous work assessing the reliability of EEG microstates from infants (26), (b) infant-caregiver dyads were required to have at least 1.5 minutes of preprocessed D-ET data for coding, and (c) the EEG and D-ET data must have been collected on the same day. The mean age of infants was 8.31 months (standard deviation = 1.53; range = 5.98-10.42) and 23 (53.49%) of them were biological males. Additional participant eligibility details are available in the *SI Appendix*, and participant demographics are available in *SI Appendix, Table S9*. All research was approved by the Duke University Health System Institutional Review Board and carried out in accordance with the Declaration of Helsinki. Caregivers provided informed consent and compensation was provided for their participation.

EEG Data Collection, Preprocessing, and Microstate Analysis. Infants sat on their caregiver's lap and watched up to 15 minutes of dynamic, relaxing videos with sound while 128-channel EEG (Electrical Geodesics, Eugene, OR) was recorded at 1000 hertz (Hz). Preprocessing was performed with EEGLAB (63) in MATLAB (MathWorks, Natick, MA). Details about EEG data collection and preprocessing are published in Bagdasarov et al. (26) and summarized in the *SI Appendix*. Quality control (QC) was performed (see *SI Appendix, Table S10* for descriptive statistics) and participants whose data did not pass QC criteria (e.g., at least four minutes of preprocessed data) were excluded (see the *SI Appendix for QC criteria)*. Each remaining participant's data was cut to include only the first four minutes to reduce potential effects of varying data lengths on brain-behavior analyses. The preprocessed data were submitted to Cartool (64) and spatially filtered to remove topographic outliers and smooth topographies (65).

Microstate analysis using polarity-invariant *k*-means clustering (66) with resampling (26, 27, 29, 67) was performed in Cartool following the procedure published in Bagdasarov et al. (26) and summarized in the *SI Appendix*. An aggregate measure of six independent statistical criteria – the meta-criterion (35, 37) – determined the optimal number of microstates at both individual and group levels. Each time point of each participant's preprocessed, spatially-filtered data was assigned a group-level microstate (i.e., backfitting procedure with a minimum spatial correlation of .50) and the average duration of microstate 4 was calculated for each participant. Prior work has shown microstate duration to be the most reliable temporal property regarding both its stability across EEG data durations for all microstates and internal consistency for microstate 4 specifically (26). Also, microstate duration has also shown the strongest test-retest reliability in adults (30). Further, only one temporal property was chosen in order to reduce the number of statistical tests run.

D-ET Data Collection and Coding. Caregivers and their infants sat across from each other at a small table and wore a head-mounted eye tracker built by Positive Science, LLC (Rochester, NY). Caregivers wore glasses while infants wore a comfortable hat, each with an infrared camera pointed to their right eye and a scene camera capturing their first-person view with 90° of visual angle (8). The D-ET calibration procedure is described in the *SI Appendix*. See Fig. 4 for D-ET setup.

D-ET was recorded at 30 Hz (i.e., 30 frames per second) while caregivers and their infants engaged in approximately four, one-minute periods of natural free play with one of two sets of three small, age-appropriate toys (e.g., rubber octopus, plastic plane). The order of sets was counterbalanced across trials (i.e., ABAB). This number of sets and toys was chosen to encourage infants to demonstrate different facets of their visual attention (e.g., orienting, shifting, and sustaining attention), and it is in line with previous work using a similar procedure (14, 59,

68). Caregivers were instructed to play as they naturally would at home for the duration of the four minutes. D-ET ended earlier than four minutes if the infant became fussy and/or cried. One experimenter operated the D-ET recording computer and monitored data collection in real time (Experimenter 1 in Fig. 4). Another experimenter switched the toy sets every minute and placed toys back onto the table if they fell off (Experimenter 2 in Fig. 4). A third experimenter sat directly behind the infant to prevent them from touching their D-ET hat (Experimenter 3 in Fig. 4). All experimenters were out of view of the infant during active data collection. Also, all experimenters and caregivers (but not infants) wore a face mask as part of the university's COVID-19 health and safety precautions. For consistency, face masks were worn even after precautions were lifted.

A team of trained research assistants coded the exact location of the caregiver's and infant's gaze frame-by-frame as indicated by a crosshair in Noldus' Observer XT (69). Descriptive codes are provided in the *SI Appendix*. D-ET data was coded only if at least 1.5 minutes of good data was provided by the infant-caregiver dyad. This was determined as data without infant fussiness and/or crying or issues with the corneal reflection which can interfere with D-ET accuracy (70). Infant-caregiver dyads had a mean of 4.27 minutes of D-ET data (standard deviation = 0.38; range = 3.10-5.11). The training procedure for coders is described in the *SI Appendix*. To ensure sustained reliability after training, 20% of all D-ET sessions of the larger study were coded twice (infant kappa mean = .84, standard deviation = .06; caregiver kappa mean = .84, standard deviation = .05; see the *SI Appendix* for details).

The coded data were read into R (71) and the following variables were quantified using custom scripts: (a) rate per minute of infant-led joint attention to toys (i.e., when infant looked at toy first), (b) rate per minute of caregiver-led joint attention to toys (i.e., when caregiver looked at toy first), (c) rate per minute of attention shifts that the infant made between anything in the environment, and (d) average duration in seconds of infant sustained attention to toys. A bout of joint attention was defined as the continuous alignment of caregiver and infant fixation within the region-of-interest for a single toy that lasted longer than 500 milliseconds but that could include looks briefer than 300 milliseconds elsewhere (14). A bout of sustained attention was defined as the continuous fixation within the region-of-interest for a single toy without any looks elsewhere for longer than three seconds (14). Additional details about how variables were quantified are available in the *SI Appendix*.

Statistical Analysis. Four hierarchical regression models were run in R with microstate 4 duration as the dependent variable. The first step always included age in months and the time of EEG data collection (0 = morning, 1 = afternoon), which were both correlated with microstate 4 duration (*SI Appendix, Table S11*). The second step included one of the four independent variables of interest: infant-led joint attention rate (model 1), caregiver-led joint attention rate (model 2), infant attention shifts rate (model 3), or infant sustained attention duration (model 4). Model change statistics assessed whether the second step improved each model's performance. For each model, multivariate outliers were identified by the Minimum Covariance Determinant (72) and removed. All models met regression assumptions. Analyses were performed without removing outliers, too (*SI Appendix*). To minimize the Type 1 error rate, a Bonferroni-correction (73) for four comparisons (i.e., the total number of models) was applied to the p value of each omnibus F test of each full model, which tested the overall significance of the complete set of predictors (*SI Appendix, Tables S12 and S13*).

Data Availability. Raw and preprocessed EEG data are available in the Brain Imaging Data Structure (BIDS) format (74) on OpenNeuro (75) (OpenNeuro Accession Number: ds005343; https://openneuro.org/datasets/ds005343/). Data and scripts for statistical analyses as well as the coded eye tracking data are available on GitHub (https://github.com/gaffreylab/Infant-Microstates-and-Attention/). Video data are not available to maintain the privacy of participants. All other data and scripts are available upon reasonable request at the discretion of the corresponding author.

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Figures and Tables

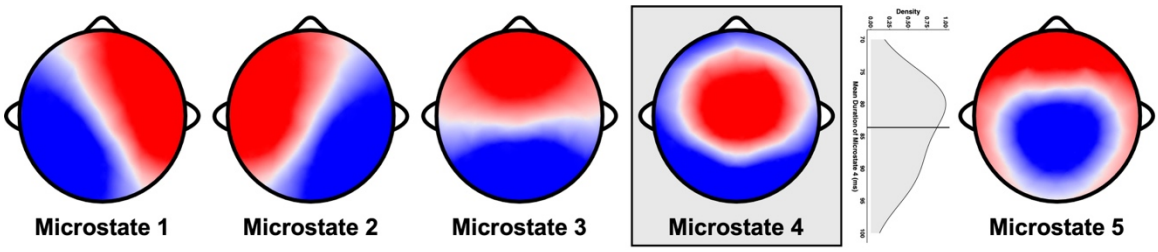

Fig. 1. The five polarity-invariant infant EEG microstates. Together, they represented 73.43% of global explained variance at the group level and a mean of 57.76% (standard deviation = 2.69%; range = 53.51-64.50%) of global explained variance at the individual level after the backfitting procedure was performed. Microstate 4, which is highlighted in grey, represented 8.65% (standard deviation = 2.77%; range = 3.37-14.70%) of the global explained variance at the individual level after the backfitting procedure was performed. The distribution of the mean duration of microstate 4 is displayed to the right of microstate 4. The black vertical line represents the mean of the distribution.

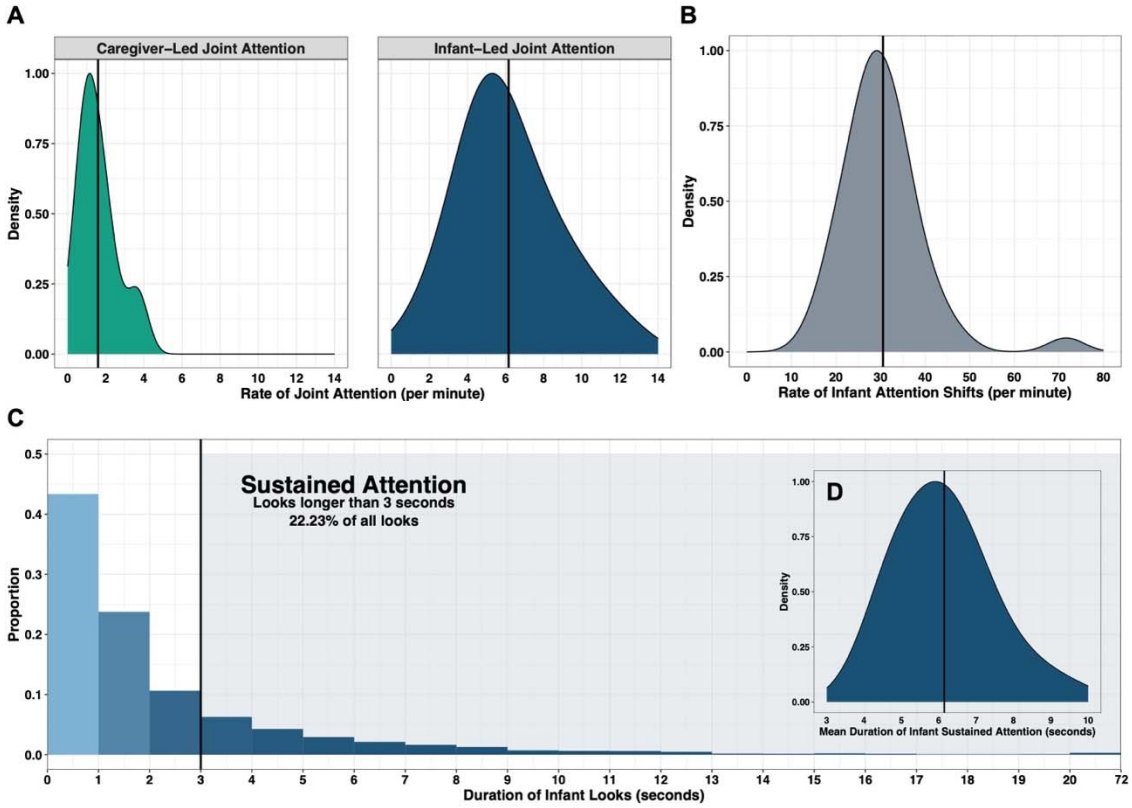

Fig. 2. Distributions of D-ET variables. The black vertical lines displayed in A, B, and D represent the mean of the distribution. The black vertical line displayed in C represents the three-second mark. (A) Rate per minute of caregiver- and infant-led joint attention. (B) Rate per minute of infant attention shifts. (C) Distribution of all infant looks (*n* = 7,765). Sustained attention represented 22.23% of all infant looks (*n* = 1,751). A handful of looks (*n* = 24) were longer than 20 seconds in duration and, for visualization, they were lumped in the last bin representing 20 to 72 seconds. (D) Mean duration in seconds of infant sustained attention.

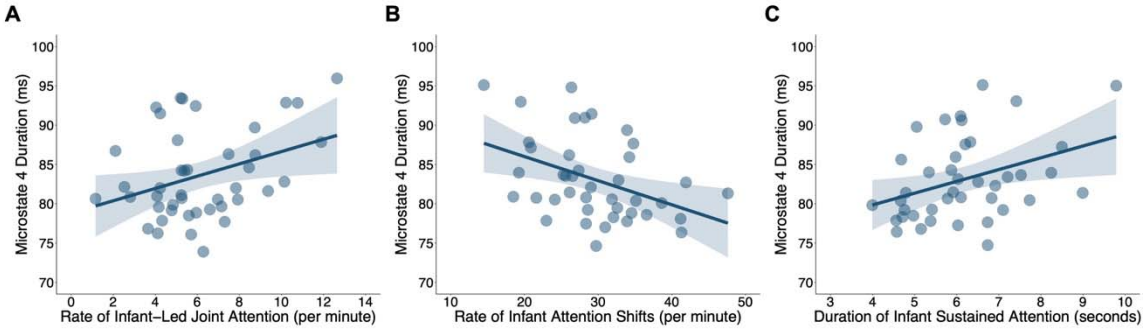

Fig. 3. Partial residual plots for statistically significant regression models showing the effect of the independent variable on microstate 4 duration (ms) while holding age and time of EEG data collection constant. The shaded band represents the 95% confidence interval. Independent variables: (A) Rate per minute of infant-led joint attention (model 1). (B) Rate per minute of infant attention shifts (model 3). (C) Duration in seconds of infant sustained attention (model 4).

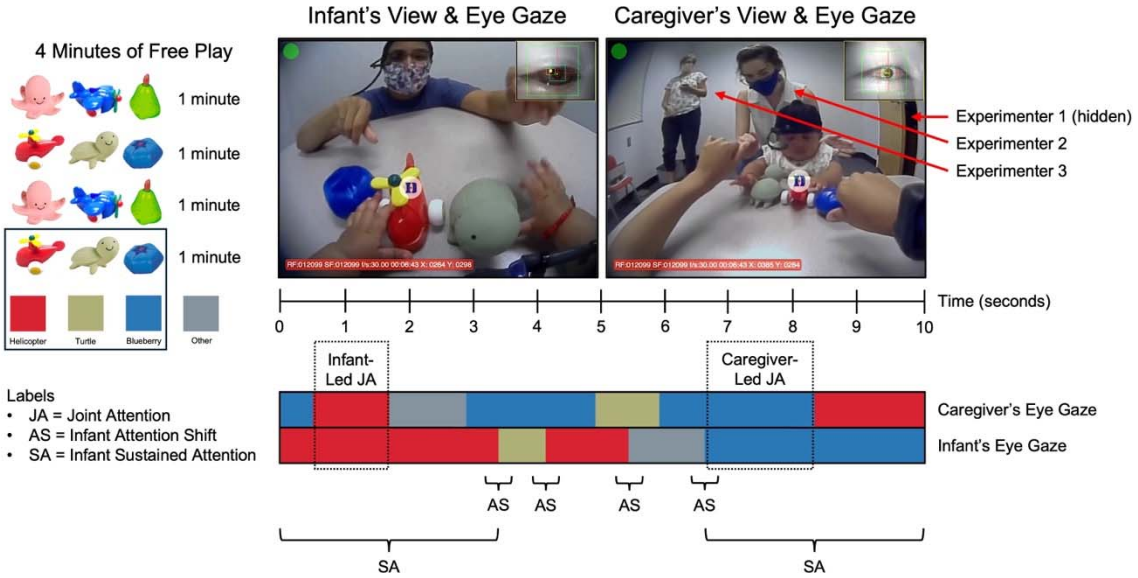

Fig. 4. D-ET setup and example codes. "Other" (i.e., the box shaded in grey) represents all gaze points other than on one of the toys (e.g., partner's face, table, etc.) for example/visualization purposes only. Participants shown here consented to using their images.