Toddler EEG Power Reflects Behavioral Social Engagement State During Naturalistic Parent-Child Interaction

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Abstract

Social engagement is a critical process for language and social development and is altered in neurodevelopmental conditions such as autism. Although previous EEG studies have investigated correlates of children's social development in closely controlled experimental studies, fewer studies have examined how the brain reflects meaningful behavioral states, such as social engagement, within naturalistic parent-child interaction. This study collected EEG from typically developing toddlers with varying language ability and their parent (n = 49, 24-44 months) during the Social EEG paradigm, which included contexts of dyadic interaction (book reading and puzzle play) and baseline (movie watching). Videos of the session were coded for social engagement using moment-by-moment, behavioral coding and applied to the EEG data. As predicted, EEG alpha power decreased ($p < .001$) and theta power increased ($p < .005$) during social engagement relative to baseline movie engagement. Further, the same pattern was replicated in an independent sample (n = 24, 25-48 months) including children diagnosed with autism. These results demonstrate for the first time that EEG power is associated with naturally occurring moments of parent-child social engagement across a range of ages, social, and linguistic abilities, opening avenues for study of more naturalistic and meaningful developmental constructs.

Keywords: EEG, Social Engagement, Naturalistic, Autism, Language

1. Introduction

A critical aim of developmental cognitive neuroscience is to elucidate the neural substrates of meaningful behaviors that support a child's engagement with the world. In particular, social engagement is an important foundation for language and social development (Adamson et al., 2019). We define social engagement as a state of shared attention between a child and caregiver; this combines two constructs described by Adamson and colleagues (2004): when a child is sharing attention exclusively with a caregiver (person engagement) or while both are actively attending to the same object and each other (joint engagement; similar to the construct of joint attention). Social engagement allows children to participate in contingent interactions and hear words in the context of heightened attention. Accordingly, children who participate in more social engagement have better language outcomes (Carpenter et al., 1998; Delgado et al., 2002; Farrant & Zubrick, 2012; Salo et al., 2018). Deficits in social engagement are defining features of autism spectrum disorder (ASD) and are linked to impairments in language development (American Psychiatric Association, 2013; Bottema-Beutel, 2016) and are often the focus of evidenced-based early intervention (Ingersoll & Schreibman, 2006; Kasari et al., 2008). However, little is known about the neural basis of social engagement and dynamically unfolding behaviors within a child-caregiver dyad.

Neural correlates of behavior as determined by measures such as electroencephalography (EEG) may be used to detect emergent developmental processes and patterns that diverge from typical development, at times even prior to their behavioral manifestation (Bosl et al., 2018). In the case of social engagement, which is often assessed via behavioral markers such as eye gaze, it is difficult to objectively measure a child's attention in the absence of sustained eye contact or directed communication. As such, assessing social engagement is especially challenging in young children and children with developmental disorders, where eye gaze and language may still be developing or used inconsistently. Neural activity assessed via EEG power could be a more direct, less demanding, and more developmentally sensitive way to study social engagement in these populations. Unlike MRI, EEG can be used in face-to-face interactive contexts, and has sufficient temporal resolution to capture rapid changes in engagement.

Previous research has aimed to investigate the brain-basis of child social development using EEG power. The EEG signal can be decomposed into frequency bands, thought to reflect populations of neurons active together during cognitive processes; the strength of this signal can be measured as power. EEG frequency bands including alpha (approximately 6-9Hz in toddlers) and theta (approximately 3-6Hz in toddlers) are associated with social information processing (Bell & Cuevas, 2012; Cuevas & Bell, 2022). Suppression (decrease relative to baseline) of alpha power has been shown to relate to social attention in infants and young children, such as viewing faces vs. objects (Nyström et al., 2011; Southgate et al., 2009). Alpha is suppressed when children viewed the face of a singing experimenter compared with objects in her hand (Jones et al., 2015) or when directed to a computer screen by an experimenter versus while viewing the screen independently (St. John et al., 2016). Similarly, enhanced theta power has been shown to correlate with social initiation, such as during moments of absent adult affect in the still-face paradigm (Bazhenova et al., 2007), and social observation, such as hearing child-directed speech or song (Jones et al., 2015; Orekhova et al., 2006; St. John et al., 2016; Stroganova et al., 1997).

Despite the promise of EEG power for studying social development, most previous research has employed highly structured experimental paradigms during observation of social stimuli rather than active participation, and with experimenters rather than caregivers. Directed attention to a screen or an actor is quite unlike real-life attention to a toy or caregiver during everyday play because it lacks reciprocity. To date, little is known about the brain-basis of the interactive, reciprocal, spontaneous and more ecologically valid process of social engagement as it naturally unfolds. In recent years, methodological advances in neuroscience research have allowed researchers to use more naturalistic contexts, such as structured games, play with toys, and conversation (Hoyniak et al., 2021; Leong et al., 2017; Liao et al., 2015; Nguyen et al., 2020; Piazza et al., 2020; Quiñones-Camacho et al., 2020; Wass et al., 2018, 2020). However, studies to date have not focused on the clinically meaningful, developmental construct of parent-child social engagement, which is uniquely important for social and language development. Instead, free play has been used to study other developmental constructs, for example, as a recovery task to study emotion regulation (Quiñones-Camacho et al., 2020). Paradigms that enable its characterization are critical for establishing neural markers of social engagement and differentiation of typical and atypical pathways.

The current study examined the neural signature of children's social engagement, employing three innovations over previous work: 1) We allowed parents and toddlers to interact naturally, using the "Social EEG" paradigm (described in detail in Norton et al., 2021) and identified moments of their social engagement, rather than manipulating social engagement through experimental stimuli or strictly controlled conditions. Although a few studies have investigated EEG power by behaviorally coding discrete markers of child attention (i.e., glances to a person vs. toy) (Jones et al., 2015; Leong et al., 2017; Piazza et al., 2020; Wass et al., 2020), no study has considered the reciprocal dynamics of states of social engagement more specifically, as defined in behavioral and clinical research. This is critical as social engagement has been shown to uniquely relate to language outcomes (Adamson et al., 2019). 2) We examined social engagement in the context in which a child most frequently engages - unstructured play with a caregiver. 3) Finally, as social engagement is an important developmental construct for language and social development, we examined the utility of predicted neural correlates in typical children across a range of language abilities as well as children diagnosed with autism. Understanding the neural basis of social engagement is a critical first step in investigating how it develops typically and is disrupted in developmental disorders.

2. Method

2.1 Overview of Approach

We investigated our research objectives in two independent samples, recruited from two larger longitudinal studies, described below. In the first study, we examined EEG power in typically developing toddlers across a range of language abilities. In the second study, we examined these questions in 12 children diagnosed with autism, and 12 age- and sex-matched typically developing peers.

Study 1. In Study 1 ($n = 49$ toddlers), we examined whether EEG power differed between social engagement and movie engagement (e.g., parent and child watch a movie together but do not engage) codes and whether this relationship varied by child language ability. We measured EEG power in two *a priori*-selected frequency bands chosen based on previous experimentally controlled studies (Hoehl et al., 2014; Jones et al., 2015; Nyström et al., 2011; Orekhova et al., 2006; Southgate et al., 2009; St. John et al., 2016; Stroganova et al., 1997). Our Question 1a focused on whether EEG power differed by engagement state; we tested the hypothesis that during moments of social engagement compared to movie engagement, children would show alpha EEG power suppression (indicating increased attention to social information), and that children would show theta enhancement (characteristic of increased cognitive effort required for social information processing) (Jones et al., 2015). Question 1b asked whether patterns of EEG activity during social versus movie engagement differed by child language ability, to assess whether this pattern was present across children of varied abilities or differed in children with language difficulties. We hypothesized that regardless of language ability, children would show alpha suppression and theta enhancement during social engagement compared to movie engagement, indicating the utility of EEG power in indexing social engagement across language abilities.

Study 2. In Study 2 (*n* = 24; 12 toddlers diagnosed with autism spectrum disorder, 12 age-matched peers), we asked Question 2: whether predicted patterns of neural activity (alpha suppression and theta enhancement for social engagement vs. movie engagement) differed for children with vs. without an autism diagnosis, as behavioral research has shown autism to be associated with less frequent social engagement than peers (Shumway & Wetherby, 2009). We predicted that when autistic children are socially engaged (per behavioral coding), they would show alpha suppression and theta enhancement during social engagement, compared to movie engagement, similar to non-autistic peers. This would indicate that neural markers can be used to study social engagement in children regardless of social ability.

2.2 Participants

All toddlers participated in the naturalistic Social EEG paradigm with their parent, as well as a battery of standardized language assessments as part of two larger ongoing studies, for which they received compensation for their time. All participants were recruited from the greater Chicago region through pediatric clinics, community childcare centers, and through print and social media advertisements. Parents provided informed consent, and all study procedures were approved by the Northwestern University Institutional Review Board. Inclusion criteria for all participants included English as the primary language spoken at home, birth at or after 37 weeks' gestation, and no additional sensory or neural impairments or diagnoses (e.g., hearing loss, epilepsy, etc.). children were excluded from participation if parents reported a premature birth (i.e., < 36 weeks' gestation), serious medical illness (e.g., epilepsy), hearing loss, or a diagnosis of a developmental disorder (e.g., autism spectrum disorder, Down Syndrome) initially or over time. Participants were also excluded if they did not pass the Modified Checklist for Autism in Toddlers Revised with Follow-Up (M-CHAT-R/F; (Robins et al., 2001, 2009) or if parents reported an autism spectrum disorder diagnosis at a later timepoint during the longitudinal study. Demographic information for children in both studies is presented in **Table 1**. Assessments were administered by trained research assistants and overseen by a certified speech-language pathologist or clinical psychologist.

Study 1 Participants.

Study 1 is comprised of a social EEG analytic sub-sample (*n* = 49 of is derived from a blended cohort followed longitudinally known as the When to Worry Study (*n* = 410). The initial study recruited children at the transition to toddlerhood, with oversampling of irritability to enrich for early mental health risk around the child's first birthday. The expanded study enriched the study for language delay by enrolling an additional sample of late-talking toddlers at age 2 (Krok et al., 2022; LaTourrette et al., 2023). As such, the percentage of late-talking toddlers in the study exceeds the estimate of prevalence of 18-20% in the general population (Reilly et al., 2007; Rescorla, 2011; Zubrick et al., 2007).

EEG data from 49 toddlers with varying language abilities were processed to test these initial hypotheses and validate the Social EEG paradigm. In a lab visit, children completed a battery of standardized assessments, including the Mullen Scales of Early Learning (MSEL)

(Mullen, 1995) as the primary indicator of their language ability, followed by EEG.

Only toddlers with usable EEG data were selected for the current analyses; one child dataset that was pre-processed was not included in the final analysis because it did not meet criteria for enough clean data (see *Selecting Epochs for Analysis* below). This current analytic sub-sample did not vary from the full study sample in terms of child biological sex (p = .13), income-to-needs ratio (p = .17) or language ability (p = .75).

Study 2 Participants.

Study 2 included children from an independent study focused on the refinement of the Social EEG paradigm in typical and autistic children (n = 24). Children diagnosed with autism met criteria on the relevant Autism Diagnostic Observation Schedule (ADOS-2; Rutter, 2012) module and participated before beginning an intervention with their parent. In Study 2, typically developing children received a passing score on the M-CHAT-RF and the Screening Tool for Autism in Toddlers and Young Children (STAT; Stone & Ousley, 2008) and had no first- or second-degree relatives with an autism diagnosis. In the lab, children in Study 2 completed the Preschool Language Scales-Fifth Edition (PLS-5; Zimmerman et al., 2011). For Study 2, usable EEG data were obtained from 12 autistic toddlers and those were compared with data from 12 approximately age- and sex-matched typically developing toddlers. A total of 50 toddlers were enrolled in this arm of the study; 10 were not able to be fitted with EEG caps or removed the caps during the experiment and 16 did not have enough clean EEG data for analysis.

2.3 Social EEG Procedure and Coding

Studies 1 and 2 used the same EEG hardware and software (collected in two lab spaces), as well as the same paradigm/procedures, described below. The Social EEG paradigm is described in detail in Norton et al. (2021); an overview is provided here. Toddlers were seated in a booster chair at a table next to their parent. Toddlers and their parents each were fitted with an EEG cap. For the current study, only data from toddlers are presented; neural synchrony data will be analyzed in a future paper. A research assistant sat in the room behind the toddler at all times to facilitate transitions between activities and to prevent the toddler from touching or removing the EEG cap.

Each dyad participated in multiple interactive “contexts” designed to elicit varying levels of engagement. Parents were instructed to interact and play with their toddler as they would at home. Dyads completed 2 contexts of naturalistic interaction (8 minutes each; toddler played with puzzles and/or read interactive books with parent) and 2 contexts of movie-watching (6 minutes each; toddler quietly watched movie of their choice, either a nonsocial movie with moving and spinning objects or if parents preferred, from online sources such as YouTube or Netflix). The naturalistic interaction contexts were designed to elicit frequent moments of naturally occurring parent-child social engagement. In contrast, the movie contexts were designed to have the dyad experience the same sensory environment but not to interact with each other. Crucially, the moment-by-moment state coding ensured that all data analyzed were from a social engagement state or movie engagement state. EEG was discontinued for children who became unduly upset or agitated, or for those who removed their EEG cap. For children who successfully completed all contexts with usable data, one movie context and one social engagement context was analyzed, selected based on visual inspection of which had more clean data. Context was tested as a covariate to ensure no differences in EEG power between moments of social engagement during puzzle and interactive book reading; see Statistical Analysis below.

Dyadic Behavioral Coding

As described above, the dyads completed various contexts designed to elicit frequent moments of engagement states of interest – social engagement and movie engagement. The paradigm was video recorded for offline behavioral coding to separate the EEG data into engagement states of interest for data analysis. Trained research assistants microcoded each context using Mangold INTERACT software (Mangold International GmbH; Arnstorf, Germany) to identify moments of each engagement state. The coding system was based on the state-based joint engagement coding scheme developed by Adamson, Bakeman, and colleagues (Adamson et al., 2004; Bakeman & Adamson, 1984). Engagement codes and corresponding criteria are found in **Table 2**. For this study, person engagement, coordinated engagement, and supported joint engagement were collapsed into one code for analysis: social engagement, as these codes both involve shared attention between a child and caregiver (Adamson et al., 2004). Object engagement during the movie context was termed movie engagement for analysis. Moments in which the child was onlooking, unengaged, off-task, or the experimenter intervened are not included in the present analyses.

Research assistants watched videos of the naturalistic EEG paradigm that included both individuals' faces and identified the beginning and ending frame of the mutually exclusive engagement states. A new engagement state code would only begin if the state lasted at least 2 seconds. Before beginning coding, each research assistant demonstrated ≥80% fidelity across 3 consecutive videos. 20 contexts were also double coded to examine ongoing inter-rater reliability, with agreement mean = 92.2% of total time (SD = 7.7%). For any context with <80% agreement (1 out of 20 contexts), the two coders met to establish agreement.

2.4 EEG Data Acquisition

EEG was recorded using two linked Biosemi ActiveTwo Systems (Biosemi B.V., Amsterdam). Recordings were made in single-ended mode that amplifies the difference between each electrode site and a common mode sensor (CMS) electrode with referencing off-line. Active Ag-AgCl electrodes were affixed to an elastic cap appropriate for the child and parent's head sizes (Electro-Cap Inc., Eaton, OH) and EEG was recorded from 32 scalp sites (Fp 1/2; AF 3/4; F 7/3/z/4/8, FC 5/1/2/6, C 3/z/4, T 7/8, CP 5/1/2/6, P 7/3/z/4/8, PO 3/4, O 1/z/2) from both participants. EEG was recorded with a low-pass hardware filter with a half-power cutoff at 104 Hz and digitized at 512 Hz with 24 bits of resolution.

A computer screen behind the participants displayed a start signal and elapsed time throughout the paradigm; a stimulus control computer sent corresponding port codes to the EEG recording computer to time-lock the video recording to the EEG recording.

2.5 EEG Data Preprocessing, Artifact Rejection, and Selecting Epochs for Analysis

EEG processing and measurement were conducted using EEGLab 14.1.1 (Delorme & Makeig, 2004) and ERPLab 7.0.0 (Lopez-Calderon & Luck, 2014) software packages. Data were imported, referenced to Cz, and high-pass filtered at 0.1 Hz (half-power cutoff). Channels with poor signal or excessive artifacts were interpolated with the average of surrounding channels using the spherical interpolation function in EEGLab; no more than 20% of total channels or 2 channels within the analytic spatial region of interest were interpolated for any participant (as in previous research with toddlers, Jones et al., 2015).

From the continuous data, 1-second non-overlapping epochs were created. The moving window peak-to-peak artifact detection function in ERPLab, with window over 200ms and 50% overlap, was used to identify trials with artifact (eye blinks or movements, muscle activity, and head/body motion), and the linear trend/variance function in EEGLab were used to identify artifacts. Accuracy of artifact rejection was visually confirmed for each participant. Thresholds were adjusted for individual subjects to obtain the most accurate rejection (Lopez-Calderon & Luck, 2014), and artifactual epochs were rejected. Random epochs were chosen from the behavioral coded “social engagement” and “movie engagement” conditions for analysis, to ensure that amount of usable data included was consistent across participants and conditions. For Study 1, 60 random epochs of each condition were selected. For Study 2, 30 random epochs per condition were selected to ensure inclusion of all usable participants, especially children diagnosed with autism; 30 is a common minimum number of epochs in previous studies (McEvoy et al., 2015; Salinsky et al., 1991).

2.6 EEG Power Calculation

Using the spectopo function in EEGLab, a fast fourier transform (FFT) with a 1-second Hamming window and 50% overlap was performed. EEG power was measured for frequency bands of interest in regions of interest that correspond to the strongest activity in that power band on the scalp: alpha (6-9 Hz in parietal electrodes P3, Pz, P4, PO3, PO4) and theta (3-6 Hz in frontal electrodes F3, Fz, F4). Relative EEG power in each frequency band was calculated as the (EEG power in the frequencies of interest)/(total EEG power in the 3-30 Hz range), averaged across the electrodes of interest. Relative EEG power was analyzed, as it is a more robust measure considering individual differences across participants (e.g., bone thickness, movement) (Marshall et al., 2002), has higher test-retest reliability than absolute EEG power (John et al., 1980), and may be more sensitive to changes in early childhood (Clarke et al., 2001) than absolute power.

2.7 Statistical Analyses

Each analysis included separate repeated measures ANCOVAs for the dependent variables. In study 1, child age in months and sex (coded 0 = female, 1 = male) were included as covariates; age was mean centered (mean for each sample subtracted from each individual score) as is recommended for within-subjects designs (Schneider et al., 2015). Because language ability is commonly associated with socioeconomic status is, we tested the correlation between family income-to-needs ratio and MSEL expressive language raw score. Income-to-needs was not significantly correlated with child expressive language in the sample ($r = .052$, $p = .720$), so it was not included as a covariate. Furthermore, the context in which social engagement codes were extracted (e.g., puzzle vs. book) was tested as a covariate. Context was not significantly related to alpha nor theta EEG power ($p > .50$, *ns*), and thus was not included in final models. In Study 2, age in months (centered) was included as a covariate; sex was not included as groups were approximately matched in terms of number of boys and girls (typical = 8 boys, ASD = 9 boys).

3. Results

3.1 Study 1

Question 1a: Does EEG Power Differ during Social Engagement Compared to Movie Engagement?

Group mean relative alpha EEG power was .33 (SD = .06) for movie engagement and .29 (SD = .04) for social engagement. Mean relative theta EEG power was .59 (SD = .08) for movie engagement and .60 (SD = .06) for social engagement. Relative alpha and theta EEG power in movie and social engagement is plotted for each individual in **Figure 1**. We used repeated measures ANCOVAs to examine the main effect of engagement code (the within-subjects factor) separately for alpha and for theta EEG power, controlling for child age and sex. The overall models were significant for both EEG alpha power ($F(1,46) = 72.82$, $p < .001$) and theta power ($F(1,46) = 46.00$, $p = .004$). As predicted, there was a main effect of condition in each case such that relative alpha EEG power decreased ($p < .001$, partial $\eta^2 = .61$) and relative theta EEG power increased ($p = .004$; partial $\eta^2 = .17$) during social engagement compared to movie engagement. (The same patterns were observed when analyzing absolute EEG power.) The covariates of age (alpha: $p = .15$, theta: $p = .37$) and sex (alpha: $p = .93$, theta: $p = .38$) were not significantly related to EEG power in either model. The observed patterns of EEG power were similar across individuals; all but 2 participants demonstrated alpha suppression during social engagement compared with movie engagement and a majority demonstrated theta enhancement.

Question 1b: Does Language Ability Influence EEG Power during Social Engagement Compared to Movie Engagement?

EEG alpha and theta power for the two conditions is plotted against expressive language ability in **Figure 2**. We conducted a mixed ANCOVA with one categorical within-subjects factor (engagement code, social vs. movie) and one continuous between-subjects factor (MSEL expressive language raw score) to assess whether child language ability influenced predicted dependent variables of alpha and theta EEG power during social engagement relative to movie engagement, controlling for child age and sex. There was no significant interaction between engagement code and language ability for alpha ($p = .47$, partial $\eta^2 = .01$) or theta EEG power ($p = .63$, partial $\eta^2 = .01$). This indicates that, during observed moments of social engagement, patterns of EEG power did not differ depending on child language ability.

3.2 Study 2

Question 2: Does EEG Power during Social Engagement Compared to Movie Engagement Differ by Child ASD Diagnosis?

We conducted a mixed ANCOVA with one within-subjects factor (engagement code) and one between-subjects factor (ASD diagnosis) to examine whether the difference between movie engagement and social engagement for alpha and for theta EEG power depended on autism diagnosis, controlling for age. **Table 3** displays mean alpha and theta values by engagement code and group. **Figure 3** displays individual alpha and theta values for all participants in movie engagement and social engagement and **Figure 4** displays mean values for the ASD and typical groups. The overall models for both alpha ($F(1,22) = 18.01$, $p < .001$) and theta ($F(1,22) = 22.67$, $p < .001$) were statistically significant. There was a significant main effect of engagement code for alpha ($p < .001$, partial $\eta^2 = .45$) and theta EEG power ($p < .001$, partial $\eta^2 = .51$), replicating Study 1 findings. There was no significant main effect of ASD status on alpha ($p = .64$, partial $\eta^2 = .01$) or theta ($p = .67$, partial $\eta^2 = .01$) EEG power or age on alpha ($p = .25$, partial $\eta^2 = .06$) or theta ($p = .94$, partial $\eta^2 = .00$). There was also no significant interaction between ASD diagnosis and engagement code on EEG power in the alpha ($p = .73$, partial $\eta^2 = .01$) or theta band ($p = .84$, partial $\eta^2 = .00$), indicating that when children with ASD demonstrate social engagement, their neural activity patterns relative to movie engagement are similar to typically developing children.

4. Discussion

The current study investigated EEG power differences associated with well-defined states of social engagement during naturalistic parent-child interaction. To our knowledge, this is the first study to examine EEG power as a correlate of social engagement during naturalistic interactions and the first to associate EEG power to varying behavioral dyadic states during unstructured interaction. Using data from natural interaction, we extended findings from previous experimentally controlled studies that show alpha suppression and theta enhancement are associated with naturally occurring moments of social engagement. Using a state-based behavioral coding approach, we observed a significant difference between social engagement and movie engagement in relative alpha (6-9 Hz) and theta EEG power (3-6 Hz) in two independent samples. In both studies, nearly all toddlers demonstrated alpha suppression and a majority demonstrated theta enhancement during naturalistic social engagement with a parent compared to baseline movie engagement. Effect sizes were large for alpha power and medium/large for theta power. Crucially, these patterns were statistically significant regardless of language ability or child ASD status. Data from this novel naturalistic approach indicate that, when toddlers with diverse social and language abilities demonstrate social engagement, their neural activity is remarkably different from non-interactive, movie engagement.

Our findings in this naturalistic paradigm are in line with previous highly controlled, experimental EEG studies that have used stimuli such as faces to invoke alpha and theta differences (Hoehl et al., 2014; Jones et al., 2015; Nyström et al., 2011; Orekhova et al., 2006; Southgate et al., 2009; St. John et al., 2016; Stroganova et al., 1997). Specifically, we replicated findings of alpha suppression indicating increased attention to social engagement (as compared to baseline which here was movie engagement) (Jones et al., 2015; Nyström et al., 2011; Southgate et al., 2009, St John et al., 2016). Additionally, we also found enhanced theta power, which is thought to index cognition related to social processing (Bazhenova et al., 2007; Jones et al., 2015; Orekhova et al., 2006; Stroganova et al., 1997), during social engagement compared to movie engagement. As a key point for clinical utility, these patterns of neural activity were found in two independent samples, diverse for developmental status, indicating their potential utility in studying emergent neural correlates of social engagement.

Results here inform our understanding of the neural underpinnings of naturalistic social engagement. Although previous studies using closely controlled, experimental paradigms have revealed information about neural activity related to social information processing, this process is very different than real-life social engagement. Activities like watching social movies, viewing video clips of experimenters singing, or observing live conditions of experimenter play do not capture the interactive, reciprocal process that is important for language and social development. Furthermore, in studies involving more naturalistic methods, analyses have yet to fully capture naturalistic social engagement. For example, in one study, EEG power was examined during conditions of parent-child puzzle play; however, parents were asked to remain silent during these interactions (Wass et al., 2018).

In other studies, markers of child attention have been examined by coding looks to people vs. objects. We know, however, that social engagement extends beyond discrete glances (Adamson et al., 2019). Moments of parent-child joint engagement are uniquely related to language outcomes beyond discrete measures of child joint attention such as eye gaze (Adamson et al., 2019). In fact, moments of supported joint engagement, in which parents scaffold interaction and children are more focused on objects than people, may be more important for language learning than moments when children are more exclusively focused on people and using use directed eye contact and language (Adamson et al., 2019). Coding moments a child looks at a person as “social” and a toy as “non-social” misses important moments of supported joint attention where a child may be looking at a toy but also attending to his mother’s language. Importantly, results here replicate and extend previous findings and extend our understanding of the neural activity underlying this important developmental process in a more true-to-life environment.

Establishing robust, reproducible neural correlates of behavior in naturalistic contexts is an important tool for studying typical and atypical mechanisms of social development in early childhood. Results here indicate the utility of EEG power in studying social engagement. When children demonstrate social engagement, the majority of children demonstrated alpha power suppression and most enhancement of theta power compared with baseline movie engagement. This was also the case for children with lower expressive language and those diagnosed with autism, suggesting that neural correlates of social engagement can be discerned even in these populations.

Once established, neural indexes of social engagement could be useful in examining social engagement in the absence of clear behavioral indicators. In some cases, neural measures may emerge or be measurable earlier than behavioral markers (Bosl et al., 2018). Could young children and those with developmental disabilities, who use little or variable eye contact, be attending more to social interactions than their eye gaze indicates? This question is especially important in developmental disorders like autism, where children may attend to parental language in the absence of overt gaze. Strikingly, our results here indicate that autistic children demonstrate neural markers of attention and cognitive processing during observed moments of social engagement, much like their typically developing peers. Our analyses were unique in analyzing EEG during moments that social engagement was observed to isolate the neural mechanisms underlying successful moments of social engagement. Future planned studies include examining behavioral and neural markers over entire contexts of interaction to determine if autistic children show fewer instances of social engagement than typically developing children and to determine if neural markers are present in the absence of behavioral indicators. In addition, we plan to examine the relation between neural correlates of social engagement and language outcomes, as well as the relation between parent and child neural activity. Ultimately, neural markers may aid in our understanding of the development of social engagement in children across a varying range of social and linguistic abilities. Naturalistic EEG paradigms are easy to complete and do not require children to follow explicit directions, which is a challenge to more traditional EEG methods.

4.1 Limitations

As one of the first studies to use EEG during naturalistic parent-child interaction, there are some important limitations to this work. We compared EEG power across two initial conditions of interest, moments of social engagement and moments of object engagement to a baseline movie (thought to reflect the brain closest to a "resting" state). Accordingly, alpha suppression and theta enhancement are relative and likely influenced by both lack of attention and cognitive effort in movie engagement (or other near "resting" states) and increased attention and cognitive effort in social engagement. Future aims include investigating how specific alpha and theta change are to social engagement, for example, in comparison to solo toy play, and whether EEG power is influenced by specific types of social engagement (i.e., supported vs. coordinated joint engagement). Further, in our second study, we analyzed a smaller number of epochs than in Study 1 (30 vs. 60 epochs) to include children with autism who have fewer moments of social engagement. Although 30 epochs is a common minimum of epochs in previous child EEG studies (McEvoy et al., 2015; Salinsky et al., 1991), this may contribute to a lower signal-to-noise ratio. Finally, we aimed here to define EEG correlates of established social engagement, and, thus, choose to examine these skills in children 25 and 48 months at a time where social engagement are thought to stabilize development (Adamson et al., 2014). In the future, these correlates could be used to examine developing social engagement in younger toddlers and infants. It may be the case that children with autism vary more from typical children at these younger ages.

4.2 Conclusion and Future Directions

These findings lay a crucial foundation for evaluating neural patterns underlying naturalistic social engagement in early childhood. Neural markers of social engagement hold promise for elucidating neural substrates of social development in children across a range of ages and social and linguistic abilities and to detect emergent signs of risk, potentially even prior to evident behaviorally. This lays the groundwork for broader application of the Social EEG approach in a range of samples and populations, with greater flexibility than experimental paradigms. First, our naturalistic approach is promising for expanding reach and ecological validity of research on neurodevelopmental mechanisms. Naturalistic tasks that elicit more true-to-life behaviors are more representative of the social interactions that toddlers and their parents engage in and to those that may go awry in neurodiverse populations. Additionally, input could be solicited from diverse caregivers in the design of naturalistic contexts to ensure ecological validity, as we have done with behavioral assessments (Barlaan et al., 2023).

Second, the discovery that EEG correlates of naturalistic social engagement can be reliably detected using naturalistic paradigms sets the stage for enacting naturalistic, dyadic EEG with joint measurement of both parent and child. This would shed further light on *dyadic engagement* which may be informative for risk and resilience factor identification. We have continued to collect this data in more dyads and collect data longitudinally. We plan to work to implement advancements in automated pediatric EEG processing (Debnath et al., 2020; Gabard-Durnam et al., 2018) and are currently analyzing joint EEG data to investigate neural synchrony within parent-child dyads (e.g., Kayhan et al., 2022).

FIGURES AND TABLES

Table 1
Demographic Characteristics of Toddler Participants in Study 1 and Study 2

	Study 1 (*n* = 49)	Study 2 (*n* = 24)	
		Typical (*n* = 12)	ASD (*n* = 12)
Age in months mean (SD)	31.4 (6.2)	33.1 (4.6)	35.6 (6.8)
Age range (months)	24-44	26-41	25-48
Sex (% male)	65.3%	66.7%	75.0%
Family income-to-needs ratio	5.4 (4.5)	6.1 (1.2)	4.3 (2.0)
Expressive language age equivalent (months)	32.9 (12.1)	40.6 (4.7)	23.3 (7.2)
Race			
Black/African American	12.2%	0%	0%
White	77.6%	91.7%	75.0%
More than one race	10.2%	8.3%	16.7%
Unknown/not reported	0%	0%	8.3%
Ethnicity			
Hispanic/Latino	6.1%	16.7%	50.0%
Not Hispanic/Latino	91.8%	83.3%	41.7%
Unknown/not reported	2.0%	0%	8.3%

Table 2

Joint Engagement Coding Scheme (Adapted from Adamson et al., 2004).

Code	Description	Example
Coordinated Joint Engagement[a]	The parent and child were actively engaged with the same object and the child was actively and repeatedly acknowledging the parent's participation, including with sustained visual interest or directed language.	The parent and child were jointly engaged in play with a puzzle, taking turns, and directing eye gaze and language towards each other.
Supported Joint Engagement[a]	The parent and child were engaged with the same object, but the child's engagement was asymmetrical and nearly exclusively on the object rather than the parent.	The parent and child were playing with a ball; the child took turns rolling the ball but was focused on the movement of the ball rather than the parent.
Person Engagement[a]	The parent and child were mutually and exclusively engaged with each other, without any objects.	The parent and child were playing peek-a-boo.
Parallel Object Engagement[b]	The parent and child were actively involved with the same object or activity, but without any social interaction.	The parent and child were both looking at the computer and watching a movie but were not interacting with each other.
Separate Object Engagement[b]	The parent and child were actively involved with different objects or activities without any social interaction.	The parent was filling out forms while the child watched a movie.
Onlooking	One partner watched the other partner's activity without engaging.	The parent was observing the child as the child watched a movie or the child watched the parent fill out a form.
Unengaged	One partner was uninvolved with any objects, people, or activities.	The parent looked around the room distractedly or the child demonstrated self-stimming behaviors with his/her hands.
Interruption	The study was interrupted for any reason.	The experimenter entered the room to add gel to the child's cap.

Note: [a] indicates a code combined into the Social Engagement condition for analysis, [b] indicates a code combined into the Movie Engagement condition; other codes were not analyzed here.

Table 3

Mean Relative Power for Alpha and Theta Power by Engagement Code and ASD Group, Controlling for Age (n = 24).

		Mean relative EEG power (SD)	
Frequency Band	Engagement Code	Typical (*n* = 12)	ASD (*n* = 12)
Alpha Power	Movie Engagement	.34 (.02)	.33 (.02)
	Social Engagement	.30 (.01)	.28 (.01)
Theta Power	Movie Engagement	.55 (.02)	.54 (.02)
	Social Engagement	.59 (.02)	.58 (.02)

Notes: Means are displayed controlling for age. Relative alpha power is calculated as the (power in 6-9 Hz) / (total power in the 3-30 Hz range), averaged across posterior electrodes. Relative theta power is calculated as the (power in 3-6 Hz) / (total power in the 3-30 Hz range), averaged across frontal electrodes.

Figure 1

Plots of relative alpha power (left panel) and relative theta power (right panel) for movie engagement and social engagement for every individual in Study 1 (n = 49).

Note. Lines represent each individual child's relative power for the movie engagement and social engagement conditions. The bolded line indicates the group mean.

Figure 2

Scatterplots displaying the relation between EEG alpha (upper panel) and theta power (lower panel) difference and expressive language raw score.

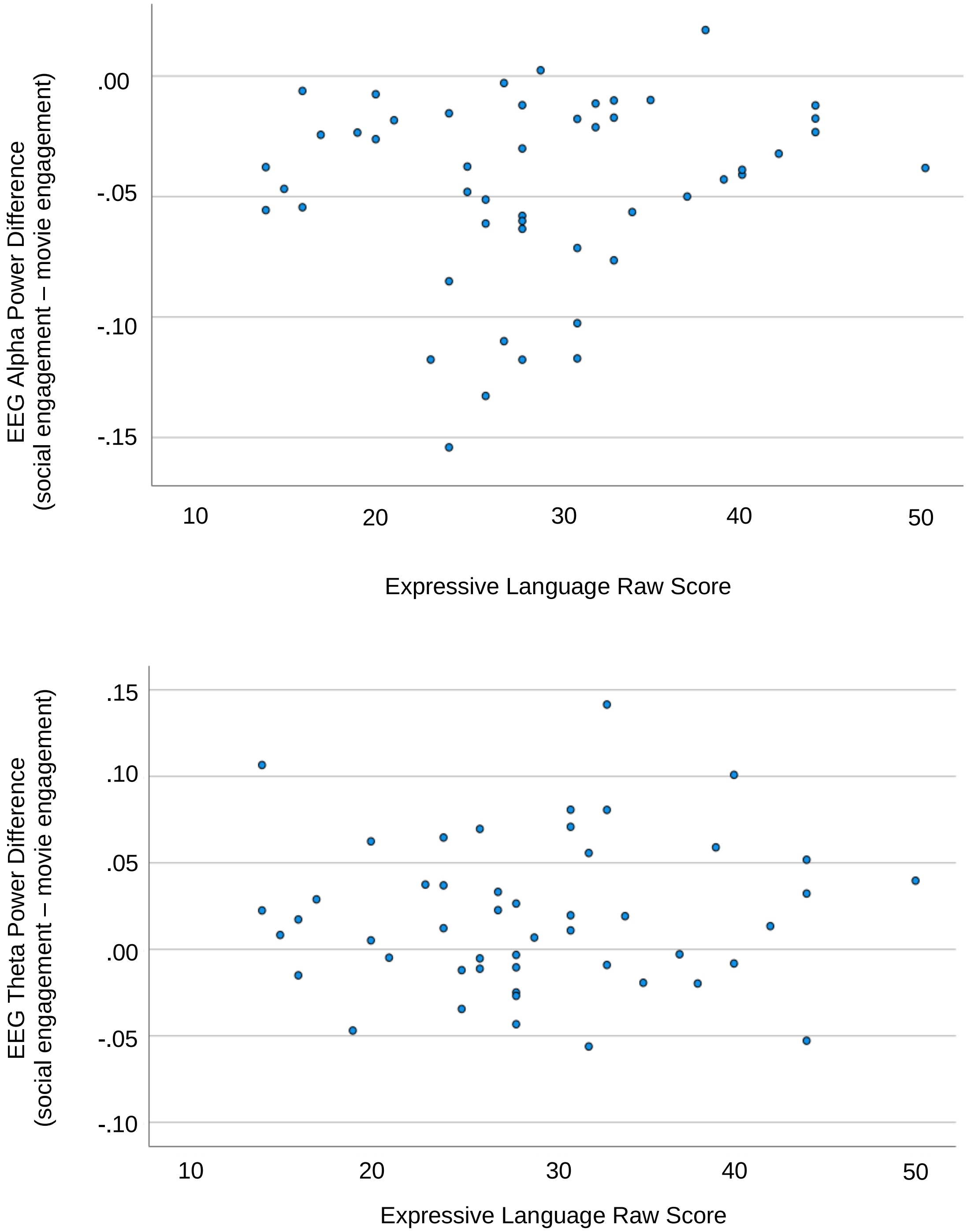
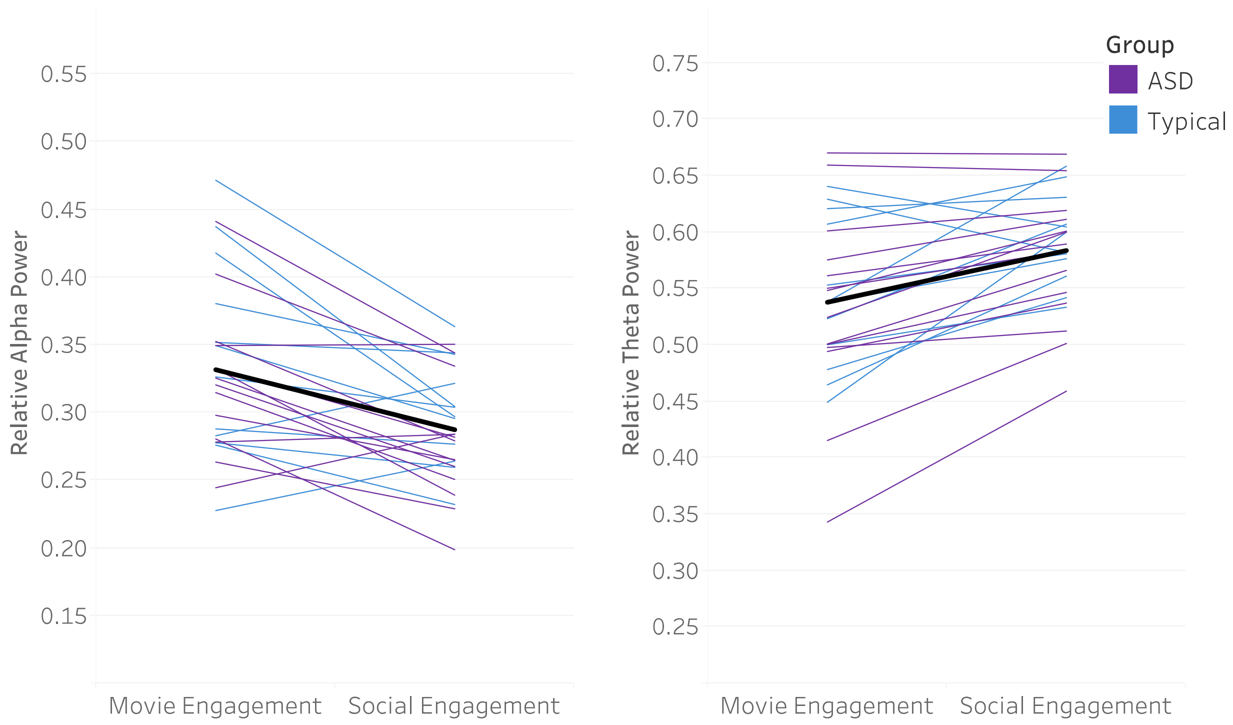


Figure 3

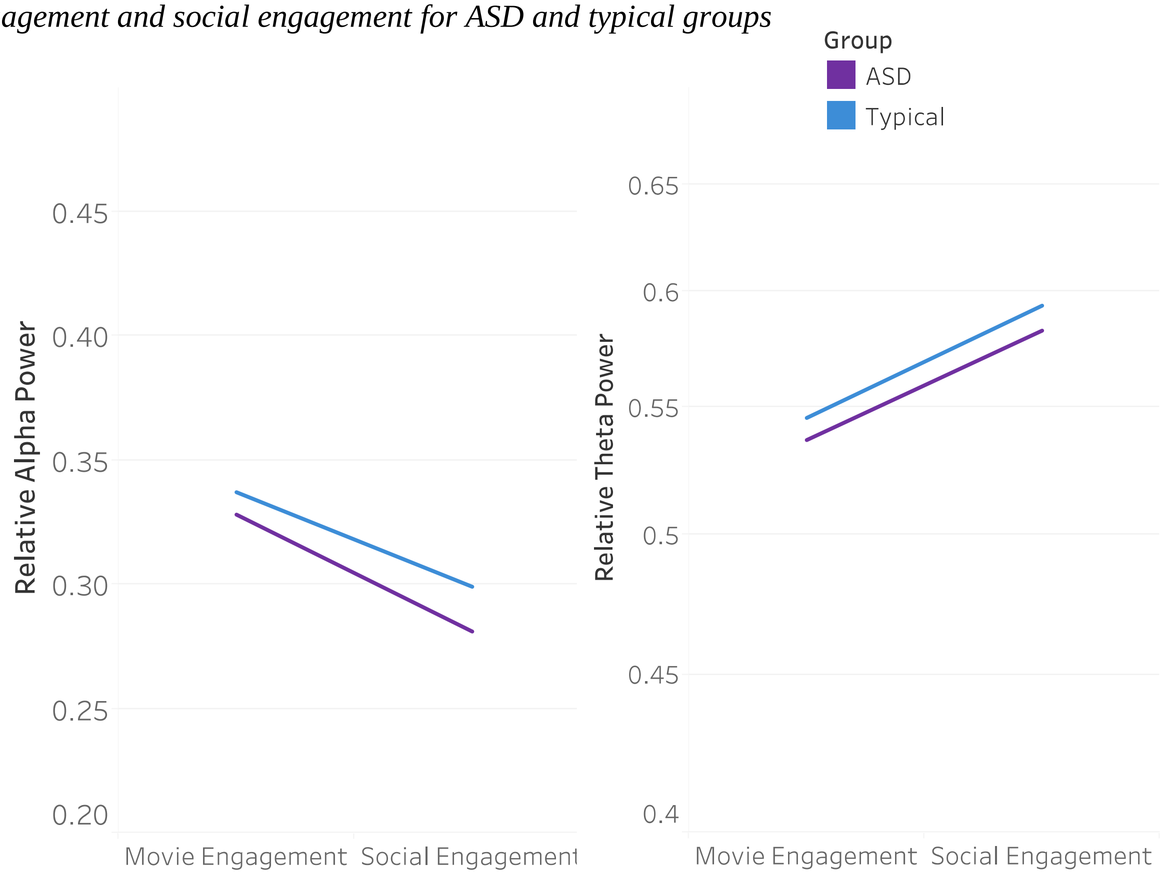
Plots of relative alpha power (left) and relative theta power (right) for movie engagement and social engagement for every individual in Study 2 by ASD diagnosis status (n = 12 per group).



Note. Bold black line indicates the mean (across all participants) power values for movie engagement and social engagement.

Figure 4

Plots of mean relative alpha power (left) and mean relative theta power (right) for movie engagement and social engagement for ASD and typical groups



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