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Complete List of Authors:	Norton, Elizabeth; Northwestern University, Communication Sciences and Disorders; Northwestern University, Institute for Innovations in Developmental Sciences and Department of Medical Social Sciences Manning, Brittany; Northwestern University, Communication Sciences and Disorders Harriott, Emily; Northwestern University, Communication Sciences and Disorders; Northwestern University, Institute for Innovations in Developmental Sciences and Department of Medical Social Sciences Nikolaeva, Julia; Northwestern University, Communication Sciences and Disorders Nyabingi, Olufemi; Northwestern University, Communication Sciences and Disorders Fredian, Kaitlyn; Northwestern University, Institute for Innovations in Developmental Sciences and Department of Medical Social Sciences Page, Jessica; Northwestern University, Communication Sciences and Disorders; Northwestern University, Institute for Innovations in Developmental Sciences and Department of Medical Social Sciences Krogh-Jespersen, Sheila; Northwestern University, Institute for Innovations in Developmental Sciences and Department of Medical Social Sciences MacNeill, Leigha; Northwestern University, Institute for Innovations in Developmental Sciences and Department of Medical Social Sciences Roberts, Megan; Northwestern University, Communication Sciences and Disorders Wakschlag, Lauren; Northwestern University, Institute for Innovations in Developmental Sciences and Department of Medical Social Sciences
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Social EEG: A novel neurodevelopmental approach to studying brain-behavior links and brain-to-brain synchrony during naturalistic toddler-parent interactions

Elizabeth S. Norton[1,2], Brittany L. Manning[1], Emily M. Harriott[1], Julia I. Nikolaeva[1],
Olufemi S. Nyabingi[1], Kaitlyn M. Fredian[1], Jessica M. Page[2], Sheila Krogh-Jespersen[2],
Leigha A. MacNeill[2], Megan Y. Roberts[1,2], & Lauren S. Wakschlag[2]

1. Roxelyn and Richard Pepper Department of Communication Sciences and Disorders, Northwestern University, Evanston, Illinois, USA.

2. Department of Medical Social Sciences and Institute for Innovations in Developmental Sciences, Feinberg School of Medicine, Northwestern University, Chicago, Illinois, USA.

Author Note:

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Corresponding Author: Elizabeth S. Norton, Northwestern University, Frances Searle Building, 2240 Campus Drive, Evanston, IL 60208. Phone: (847) 491-2519. Email: enorton@northwestern.edu

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Abstract

Despite increasing emphasis on emergent brain-behavior patterns subserving language, cognitive, and socio-emotional development in toddlerhood, methodologic challenges impede characterization. Toddlers are notoriously difficult to engage in brain research, leaving a developmental window in which neural processes are understudied. EEG and ERP paradigms at this age typically employ structured, experimental tasks that rarely reflect formative naturalistic interactions with caregivers. Here, we introduce and provide proof of concept for a new "Social EEG" paradigm, in which parent-toddler dyads interact naturally during EEG recording. Parents and toddlers sit at a table together and engage in different activities, such as book sharing or watching a movie. EEG is time-locked to the video recording of their interaction. Offline, behavioral data are microcoded with mutually exclusive engagement state codes. From 216 sessions to date with two-year-old toddlers and their parent, 72% of dyads successfully completed the full EEG paradigm, suggesting that it is possible to collect dual EEG from parents and toddlers during naturalistic interactions. In addition to providing naturalistic information about child neural development within the caregiving context, this paradigm holds promise for examination of emerging constructs such as brain-to-brain synchrony in parents and children.

Keywords: EEG, parent-child interaction, synchrony, hyperscanning, neurodevelopment

Young children develop cognitive, language, and socio-emotional skills through rich, reciprocal interactions with caregivers, yet neuroscience methods typically study the neural correlates of these developmental processes in solitary, rather unnatural experimental settings. Electroencephalography (EEG) allows researchers to examine the moment-by-moment natural electrical activity of the brain while a child is in a given state such as rest, or in response to various types of stimuli or conditions. Because it provides a temporally precise signal, can be portable, and is rather tolerant of motion, EEG has been widely used to examine development and brain-behavior associations in infants and children and has provided key insights into a variety of developmental processes (reviewed in Anderson & Perone, 2018; Bell & Cuevas, 2012). Despite these benefits and advances, however, the vast majority of EEG research does not reflect the naturalistic social interactions with a caregiver that facilitate development. Identifying the neural correlates that underlie specific social and communicative behaviors that occur during parent-child interactions holds great promise for providing more ecologically valid scientific findings regarding the neurobiological processes of development (Rolison et al., 2015; Suveg et al., 2016). Further, the opportunity to study brain-to-brain neural synchrony during naturalistic social interaction could provide new insights, particularly into social development, given the importance of behavioral and physiological synchrony (DePasquale, 2020; Konvalinka & Roepstorff, 2012; Lunkenheimer et al., 2020; Quiñones-Camacho et al., 2020).

In this paper, we first provide background on current social neuroscience methods for studying development along a continuum of naturalness with commentary on related advantages and challenges that the field currently faces. The paper first describes how studying the brain during parent-child interactions can be uniquely informative, especially when examining naturally occurring behaviors among the dyad. Additionally, we review some of the benefits of studying interpersonal neural synchrony and its contributions to our understanding of child development. We introduce a paradigm that we have developed called Social EEG, designed to assess parent and child neural signals as well as their synchrony, during naturalistic interaction. Social EEG uses state-based behavioral coding to identify naturally occurring behaviors in true-to-life social interaction in order to examine their neural correlates. Here, we also provide data on the rates of success for the paradigm and initial usability in order to evaluate its utility.

Use of EEG in Developmental Research

EEG is a common brain measure used to study infants and children, partly because, in contrast to magnetic resonance imaging (MRI), it is more tolerant of motion, can be done in a child-friendly room with the parent or researchers present for comfort, and is relatively low-cost (Bell & Cuevas, 2012; Gilmore et al., 2018). Functional near-infrared spectroscopy (fNIRS) is another noninvasive brain measure used with young children because of similar advantages (Gervain et al., 2011), but its temporal resolution is poor relative to EEG. Both because of its temporal resolution and the well-established understanding of correlates of certain EEG power bands (e.g., Koenig et al., 2002; Marshall et al., 2002), EEG lends the opportunity to meaningfully examine time-sensitive brain-behavior associations in populations that are typically difficult to study with brain measures, including infants, toddlers, and young children who experience difficulty with communication and language (McWeeny & Norton, 2020). In this way, EEG has the potential to help "close the gap" that currently exists in which infants and older preschoolers are characterized in brain studies, but toddler age is often skipped, because it can be difficult to obtain MRI either during natural sleep or while the child is awake (Zhang et al., 2019).

Resting state is among the most common methods applied to EEG research with young children. These paradigms are designed to assess intrinsic neural activity without a specific task or stimulus. In classic resting state paradigms with adults, a participant sits quietly with their eyes closed in order to capture neural activity in a state as close to true "resting" as possible. For toddlers and young children, resting paradigms have been adapted to record continuous EEG while children are presented with minimally stimulating objects or events, such as watching a neutral, child-friendly video (e.g., McEvoy et al., 2015; Simon et al., 2017), a spinning bingo wheel (e.g., Marshall et al., 2004), or the blowing of bubbles (e.g., Gabard-Durnam et al., 2019; Tierney et al., 2012).

Measures from resting or near-resting state in children can be used to study the social brain by examining naturally occurring patterns of brain activity without task demands or by continuously recording data while children passively view stimuli related to a behavior or mental state of interest. Resting state studies have revealed important insights into neural correlates and development that support infant and toddler development in social behaviors (Paulus et al., 2013), the influence of maternal behavior during parent-child interactions on child cognition (Bernier et al., 2016; Liu et al., 2020), variation in language and cognitive abilities (Bell & Fox, 1992; Benasich et al., 2008; Gou et al., 2011; Tarullo et al., 2017), in addition to revealing differential brain activation particularly among children with social communication difficulties such as autism spectrum disorder (Bernier et al., 2007; Murias et al., 2007; Wang et al., 2013), and language and learning disorders (Schiavone et al., 2014).

In order to study social development in children, some studies have investigated differences in neural activity between distinct passive-viewing conditions, such as those with versus without social stimuli. For example, studies have presented video recordings of agematched peers performing a task (van Elk et al., 2008) or videos of an experimenter demonstrating social actions (Jones et al., 2015) during EEG recording. Including both baseline and passive-viewing conditions offers added informative value in that these studies can capture children’s baseline brain response relative to manipulated social contexts in order to parse out baseline-state neural mechanisms from the neural mechanisms that may be uniquely involved in processing socially relevant information.

Toward Naturalistic EEG Paradigms with Children in Developmental Context

Studying social development using structured stimuli, during passive viewing, or at rest, although valuable, does not allow for examining the child’s naturally occurring behavior. Some researchers have developed approaches to bringing more true-to-life, dynamic qualities of the social world to the laboratory during EEG in part by expanding beyond presenting repeated stimuli via a computer. These include having an in-person interaction with the participant in real-time by playing peek-a-boo or directly speaking or singing to the child (Goodman et al., 2020; Jones et al., 2015; Leong et al., 2017; Orekhova et al., 1999; 2006; Ruysschaert et al., 2013; Shimada & Hiraki, 2006; St. John et al., 2016; Stroganova et al., 1997). Yet even with these methodological adaptations that aim to move toward stimuli more relevant to the child’s own social context, the socialization being captured is still somewhat restricted in that it does not give children the opportunity to freely navigate interactions as they normally would in real-world contexts outside of the laboratory. By examining changes in EEG brain activity with paradigms that are more closely aligned with dyadic, naturalistic interaction, research is likely getting closer to pinpointing the neural mechanisms that underlie more complex, live social communication that children are experiencing in their daily lives.

Studying the Brain During Parent-Child Interaction

The parent-child context is considered the most formative experience of early childhood for shaping neurodevelopment and has long been captured in developmental science behaviorally (Kochanska & Aksan, 2004; Wakschlag & Hans, 1999). However, characterization of the brain during this process has largely been lacking. Though scientific advancements toward naturalistic neuroscience continue to provide meaningful information, we, and others (Bell, 2020; Dumas et al., 2010; Hari & Kujala, 2009; Konvalinka & Roepstorff, 2012; Markova et al., 2019; Nyugen et al., 2020; Rolison et al., 2015; Schilbach et al., 2013; Wass et al., 2020), recognize an important gap in our understanding of the *interacting* developing brain, especially interaction between parents and children, complementary to typical single-participant research paradigms. Parents and their children must draw on additional skills when actively engaging in reciprocal interactions by coordinating their own internalized social cognition with the rapidly unfolding responses and expectations of their parent (or other communication partner) in real-time (De Jaegher et al., 2010; Konvalinka & Roepstorff, 2012).

One method for increasing naturalness of EEG paradigms is to directly involve parents as participants together with their children. Neuroscience paradigms incorporate parent involvement in studies by instructing parent-child dyads to jointly attend to the same videos or stimuli (Azhari et al., 2019; Krzeczkowski et al., 2020), work together to assemble a tangram or puzzle (Atzaba-Poria et al., 2017; Nguyen et al., 2020; Quiñones-Camacho et al., 2020), or play a computer game (Liao et al., 2015; Reindl et al., 2018). Paradigms have also been designed to simultaneously collect brain data from both parent and child with less restrictive study protocols that allow dyads to have greater autonomy and flexibility in the interaction. This includes giving parent-child dyads one or two toys to freely play with (Hoyniak et al., 2021; Quiñones-Camacho et al., 2020) or being instructed to play silently (Wass et al., 2018), in addition to simply having parent-child dyads freely engage in unguided verbal conversation with each other for ten minutes (Nguyen et al., 2021). Giving flexibility to these opportunities of interaction between parents and their children while collecting measurements of the brain permits children to naturally elicit behaviors and responses related to the transactions of communication. From there, researchers are better equipped to then characterize these social and communicative behaviors in the context of the underlying brain activation patterns that are simultaneously being observed.

Studying Naturally Occurring Child Social Behaviors

Another consideration in naturalistic EEG paradigms is how best to capture social constructs of interest. Most previous EEG work has examined child social processing using experimentally presented stimuli, which has the advantage of strict standardization. This can be helpful in differentiating neural mechanisms required for social processing from endogenic factors. Social processing during experimental tasks, however, widely varies from true-to-life social interaction. Additionally, in measuring a construct like joint engagement, it is difficult to control whether a child truly engages with a social partner or does not. By behavioral coding interaction, researchers are able to identify behaviors of interest as they occur naturally without strict experimental protocols that constrain how the interaction unfolds. This is especially advantageous for young children and children with disabilities who may otherwise struggle to follow directions or watch a computer screen for long periods of time.

For example, social behaviors of interest coded during studies of interpersonal neural synchrony include looking behavior (such as mutual gaze or visual attention to an object, Leong et al., 2017; Piazza et al., 2020; Wass et al., 2018), turn-taking or other aspects of conversational quality (Nguyen et al., 2020; 2021; Quiñones-Camacho et al., 2021), and participant affect (Atzaba-Poria et al., 2017; Nguyen et al., 2020; Piazza et al., 2020). Interactions have also been coded more generally as synchronous or asynchronous second-by-second, taking into account several types of social actions at once (Hoyniak et al., 2021; Quiñones-Camacho et al., 2020). However, current work primarily focuses on discrete, child markers of engagement, where the constructs observed are aggregated into one, composite data point per dyad that summarizes the level of engagement for that interaction. This is in contrast to the design of the coding approach in the current paradigm, where the ongoing state of the parent and child is assessed. This is an important added methodological consideration to complement current work in this area as moments of joint engagement, which consider the timing and reciprocal nature of parent-child interaction, are uniquely related to language development above discrete measures of child attention alone (Adamson et al., 2019).

Inter-Brain Synchrony as a Method to Study Child Social Development

Another promising avenue for studying child social development is to characterize parent-child attunement during interactions at the level of behavior, physiological processes, and, especially, neural entrainment (Feldman, 2007, 2012). For example, adult participants who align the rhythm of a joint finger-tapping action (Heggli et al., 2021; Hove & Risen, 2009; Konvalinka et al., 2014) or students attending to the same lesson in the same classroom (Dikker et al., 2017) demonstrate coordination or similarity in brain activation patterns with each other. Part of what supports interpersonal coordination among interaction partners is the concept of synchrony. Social synchrony is a "dynamic process by which hormonal, physiological, and behavioral cues are exchanged" to coordinate the timing of social behaviors between partners (Feldman, 2012). Synchrony among communication partners can be observed in terms of behaviors such as joint engagement in a task, mutual gaze, and turn-taking. Greater behavioral synchrony during parent-toddler interactions has been associated with communicative competence and self-control

(Lindsey et al., 2009) and emotion-related socialization behaviors (Levy et al., 2019; Kochanska & Aksan, 2004; Lunkenheimer et al., 2020). Synchrony can also be assessed via physiological measures such as alignment in levels of cortisol (e.g., Laurent et al., 2017, Pratt et al., 2017), heartbeat rhythms (Suveg et al., 2016), and respiratory rhythms (e.g., MacNeill et al., 2021). Synchrony is generally considered to be an important factor in child development, but our knowledge of how inter-brain synchrony between children and parents relates to important outcomes is relatively new.

Investigation of the neural mechanisms underpinning these synchronous behavioral and physiological changes during parent-child interactions have only recently begun to be empirically studied in a developmental context, especially with regards to toddlerhood. Toddlers are transitioning into an increasingly active role in dialogue as they expand on their linguistic, cognitive, and socio-emotional skills to communicate more complex needs and intentions to their social partners (Bloom, 1993; Harrist & Waugh, 2002). As such, it is of growing interest to investigate not only young children's neural activity when actively engaged in interactions, as opposed to studying the brain during isolated and passive processing of social information, but to investigate dyadic brain-to-brain synchrony during rapid social and language development in toddlerhood, particularly within the caregiving context (Schilbach, 2010; Schilbach et al., 2013). Specifically, hyperscanning research, or the method of collecting brain data from two or more individuals simultaneously, permits researchers to analyze the directionality of synchronization between parents and their children, with special focus on the concurrent brain activity during interactions and play.

Moreover, single participant neuroscience essentially assumes that the stimuli presented uniquely give rise to the measured brain states, whereas stimuli that naturally arise from communication in hyperscanning studies are not fixed, rather they ecologically adapt with every social or linguistic transaction in a bidirectional manner. In fact, hyperscanning research has illuminated novel brain activation patterns that are otherwise distinct from findings in single-participant paradigms (Redcay & Schilbach, 2019; Redcay & Warnell, 2018; Schilbach et al., 2013; Wass et al., 2020). Still a growing field, these methods and analyses have already been successfully translated for use with parents and their infants (Krzeczkowski et al., 2020; Wass et al., 2018), young toddlers (Atzaba-Poria et al., 2017; Liao et al., 2015), and preschool-aged children (Azhari et al., 2019; Hoyniak et al., 2021; Nguyen et al., 2020; Nguyen et al., 2021; Quiñones-Camacho et al., 2020) across fNIRS and EEG measures. Importantly, these studies have also been able to include children with disabilities, for example children with severe physical disabilities who are nonverbal (Samadani et al., 2021).

However, to our knowledge, no published research to date has investigated parent-child EEG hyperscanning with young children to examine brain activation during naturally unfolding complex social behaviors such as joint engagement. Joint engagement is of particular interest in relation to brain-to-brain synchrony during parent-child interaction because it is established as a key correlate and predictor of language development (Adamson et al., 2019; Conway et al., 2018; Trautman & Rollins, 2006). Further, our approach, described below, is the first to apply a coding scheme to the entirety of the parent-child interaction, allowing us to analyze EEG during a variety of different behavioral states between the parent and the child. The field has yet to fully explore dyadic brain activity during unrestricted play with toddlers, especially, and their parents as it naturally unfolds, allowing for even closer ecological validity with behaviors naturally elicited during parent-toddler interactions. In the next section, we describe our "Social EEG" paradigm.

The Social EEG Paradigm

Here, we introduce the Social EEG paradigm, which was designed to examine neural activity from toddlers and their parents during face-to-face, naturalistic interaction. Unlike previous experiments which have presented social stimuli through video clips or discrete actions performed by experimenters, we aimed to measure neural activity in the child and parent as it occurs during interaction. We designed contexts to elicit frequent moments of social interaction, and for contrast, baselines without interaction. Acknowledging the fact that it is impossible to control whether or not a dyad truly interacts or does not interact, a crucial feature of this paradigm is the use of microcoding of the dyad's interaction to identify engagement states *after* data collection. This approach has several key advantages, including allowing for the analysis of data during truly naturally occurring interaction, examining neural activity during joint engagement as it is defined in the behavioral literature (e.g., Adamson et al., 2004), and recording from the parent and child simultaneously, allowing for additional analysis of inter-brain synchrony. Further, this approach allows separation of salient states and actions rather than collapsing across all interactions in a given time period. This is important, as it allows examinations of variations in synchrony that may be specific to parent-child interaction (Suveg et al., 2016).

As an overview, the Social EEG paradigm involves the toddler and parent dyad sitting together, while wearing EEG caps. The researchers instruct the parent and provide different materials to facilitate the dyad engaging in different contexts, which were designed to elicit varying levels and types of interaction. The entire session is video-recorded and the video is linked to the EEG recording. Offline after the session, the video is microcoded and the codes are applied back to the EEG data for analysis.

Social EEG Setup Procedure

The lab space for the Social EEG paradigm includes two adjoining rooms, one room where the dyad sits and the other room where the EEG acquisition computer is located. Before the parent and child arrive, materials are set up to facilitate completing the capping process as quickly as possible. For a typical session, one research assistant is solely responsible for controlling the EEG acquisition software from an adjoining room. Another one to two researchers are present for the session, depending on the experience-level of the researchers relative to capping young children (van der Velde & Junge, 2020), and consideration of the additional supports that some children may need during EEG data collection (e.g., due to individual differences in temperament or restlessness). The research assistant(s) in this role set up the caps, provide instructions to the parent, and ensure that the child does not pull on or remove the EEG cap. Regardless of the participant's level of comfort with the cap, at least one researcher stays with the child for the entirety of the session, sitting behind them once the EEG recording begins.

During the Social EEG session, the child sits in a booster chair at a table and the parent sits at a 90-degree angle, around the corner of a table (Figure 1). This setup allows a single camera angle to capture both people's faces (more so than if they were sitting directly across from each other), and for the dyad to easily interact face to face (more so than if they were sitting side by side). For the EEG cap setup, the child is given the option of watching a movie on a laptop or playing with toys. Next, a researcher explains the EEG setup to the parent and the parent is encouraged to offer suggestions that might ensure success and child comfort during the capping process. The child is familiarized with the EEG caps, gel, and plastic syringes and the process is narrated in child-friendly language. The parent is capped first in order to model the process for the child and to minimize the time between child cap fitting and data collection. The child is encouraged to touch the cap, plastic syringe, and gel to familiarize themselves with the process and is enlisted to “help” the researcher place the cap on their parent’s head or on a teddy bear. Once parent capping is complete, the researchers work to fit the child’s cap and gel the electrodes. One researcher keeps the child engaged during the capping process and offers engaging toys if the child becomes restless. The setup process is similar between 2-year-old and 3-year-old visits; however, 3-year-old children who complete the Social EEG a second time as part of the longitudinal aspect of our larger study are typically more comfortable wearing the cap, facilitating setup time.

As the cap is set up, the EEG signal is observed on the acquisition computer and offset values (indicators of quality of the connection) are lowered if needed. During the entirety of the paradigm, one researcher sits in the room next to the child to monitor the child’s hands and keep the child engaged during transitions between the contexts, in order to prevent the child from touching or removing the EEG cap. The other researcher remains in the adjacent room to monitor data quality. Once setup is complete, the dyad begins the four contexts and EEG is recorded during each context, in addition to video recording of the dyad interacting. We record from two identical linked EEG systems and record both the parent and child’s data into a single file, ensuring precise timing alignment between their data.

Social EEG Paradigm Contexts

Various contexts were designed to elicit frequent and spontaneous moments of interaction between the toddler and their parent, as well as moments without interaction (including shared and separate tasks) for comparison. The length of contexts and thus the time of EEG data collection differs, as contexts involving more social interaction (Puzzles, Books) elicit more speaking and movement, thereby requiring more time to collect enough usable data, compared to contexts that tend to yield less movement and engagement (Movie and Movie and Forms). For the movie contexts, the parent helps select a movie or show that the child will enjoy (from Netflix or Youtube) in order to maximize the child's engagement with the movie, yielding a sufficient number of epochs when the child is engaged with the movie. Giving children and parents the option to choose the movie was partly a methodological consideration for increasing child compliance, particularly after having completed 2-3 hours of behavioral assessments prior to the EEG. In parallel, the variety of movies chosen by the child mirror the variety of naturally occurring differences in social interaction that arise during the book and puzzle contexts. This design consideration is covered again in the discussion.

The four contexts are as follows:

(1) **Movie** (6 minutes): The dyad watches a child-friendly movie of their choice together. The parent is instructed to interact as little as possible with the child; the parent is allowed to respond if their child needs assistance or to redirect them to keep watching the movie if necessary. The goal of this context is to capture moments where the dyad attends to the same stimulus but are not interacting with each other. Because the child often watches a movie during cap setup, this is a more seamless transition from the setup and allows the child some additional time to warm up to the EEG session.

(2) **Puzzles** (8 minutes): The dyad is given 3-4 age-appropriate puzzles. The parent is instructed to interact with their child as much as possible, like they would at home.

(3) **Books** (8 minutes): The dyad is given a set of books that encouraged interaction (e.g., peek-a-boo books, books with flaps to look under, etc.). The parent is again instructed to interact as much as possible.

(4) **Movie and Forms** (6 minutes): For this context, the child again watches a movie of their choice while the parent fills out a form on a clipboard. The parent is again instructed to interact as little as possible. This context is designed to elicit moments where the parent and child are primarily attending to different stimuli and not to each other.

Each dyad completes the four contexts in succession, unless child fatigue or distress warrants a context to be repeated or discontinued. For example, if a child is very active and/or not attending while watching the movie (reducing available data for the relevant code), the researcher would try to repeat the movie context once more either immediately at the end of the paradigm, to ensure sufficient usable data. If a child is distressed or fatigued, both of which are undesirable for the family's enjoyment, but also often result in extremely poor data quality, the researcher discontinues the context and consults with the parent to decide the best course of action, which could include attempting a different context (with the goal of repeat the discontinued context later) or discontinuing the entire paradigm.

Microcoding of Social EEG Session

As described above, the dyads complete various contexts in order to elicit frequent, spontaneous moments of interaction between toddlers and their parents, as well as moments without interaction. Because of the naturalistic design of the paradigm, there are times that children may have been distracted or otherwise off-task during any context. We thus chose to adapt and apply a state-based joint engagement coding system that was originally designed to capture naturalistic social interaction between parents and children. The coding system is based on the state-based joint engagement coding scheme developed by Bakeman, Adamson, and colleagues (Adamson et al., 2004; Bakeman & Adamson, 1984). This coding scheme is designed to characterize a child's attention to people and objects, with a focus on parent-child joint engagement. Whereas measures of joint attention traditionally focus on discrete child skills such as initiating bids, joint engagement is a state in which a child and parent are involved with the same object or activity and reflects both partners contribution to the shared interaction (Adamson et al., 2019). Additional codes were developed specific to this paradigm, such as separate and parallel object engagement, to describe each person's attention when the dyad was not primarily interacting with each other. Additionally, unlike the original coding scheme which did not focus on the parent's activity when not interacting with the child, our coding scheme reflects both partners even when they are not interacting (for example, the child may be watching a movie while the parent is observing the child). The specific codes and corresponding definitions and examples are found in Table 2.

Offline, after the EEG session, each interaction is microcoded using INTERACT software (Mangold, 2020). The coding system allows for extraction of moments of interest (e.g., joint engagement, object engagement) and separation into respective conditions for analysis. Using this event-based coding scheme, research assistants coded the video of the entire Social EEG recording session into mutually exclusive and exhaustive engagement states; that is, every moment of the session is assigned to a code. Coders watched the videos and identified the millisecond that the engagement state began and ended. In order to be coded, engagement states need to last at least 2 seconds. If the state lasts fewer than 2 seconds, a new state is not coded. At the conclusion of each context file, the list of the behavioral states and their corresponding time (in milliseconds) is exported.

Before beginning coding, each research assistant is trained and oriented to a codebook and examples of states. Each coder must demonstrate at least 80% fidelity (i.e., that the correct codes were used within 1 second of the beginning of the engagement state) across 3 consecutive videos coded by the criterion coder (author B.L.M.). 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.

Integrating Behavior Codes and EEG Data for Analysis

An important consideration for this work is time-locking the EEG data and behavioral codes. Stimulus presentation software is coordinated with the EEG acquisition computer; the software sends port codes to the EEG recording computer that is coordinated with stimulus presentation on a computer screen behind the participants that is visible in the recording. The screen displays a mark for the onset of EEG recording for that context, as well as a time mark after every elapsed minute of the context. Behavioral coders watch the video and identify the moment the word "begin" appears on the monitor at which time they begin behavioral coding. Port codes from the EEG files are merged with behavioral codes from the INTERACT files, and the beginning port code is used to time-lock the files. Although the refresh rate of the display screen and the frame rate of the video recording will influence how closely time locked the EEG and behavioral codes will be, data analysis centers on continuous EEG over seconds-long states rather than event-related analysis, as is common in ERP work.

In order to analyze EEG data, the behavioral codes are applied as events to the EEG file that contains both participants' data. Artifacts are first identified and corrected using independent components analysis (ICA) (separately for each person) and remaining artifacts are detected and rejected. EEG data are marked with non-overlapping 1-second events for epoching, and with events corresponding to the behavioral codes (see Figure 2). Some data are discarded, including the first 500ms of all codes in order to remove the time when the dyad may not yet be in the state, and additional time that does not fit in the 1-sec epochs. (For example, for a coded state that lasted 3.83 seconds, the first 500ms would be discarded as transition time, three 1-second epochs would be included if data were artifact free, then the remaining .33 seconds that do not fit in to an epoch would be discarded.)

After this event and epoching process, EEG data are processed using a relatively typical approach. Epochs corresponding to each code of interest can be collapsed for analysis. (Codes like “Interruption” are included so that all moments fit within one of the mutually exclusive codes, but are not included in analysis.) For example, child baseline data can be examined from the object engagement epochs in both the Movie and the Movie and Form contexts. Parent-child synchrony can also be analyzed during various types of behavior as indicated by the codes. For example, we plan to compare child and parent EEG synchrony during moments of joint engagement versus parallel object engagement epochs (no interaction but shared object engagement, such as in the Movie context) and separate object engagement (no interaction and different object engagement, such as during Movie and Forms). Crucially, this approach will allow us to disentangle what degree of brain-to-brain synchrony occurs because of shared sensory input and the contribution of naturalistic, social interaction. By comparing across codes rather than entire contexts, we can extract the moments of true engagement and combine them for analysis, rather than averaging across a variety of behaviors within a longer time interval, like a context.

Feasibility Study

To illustrate the feasibility of the Social EEG paradigm, we present data from an ongoing study of young children’s language and socio-emotional development. First, we report the percent of successful sessions (child and parent were successfully capped and completed all 4 contexts without significant movement or fatigue precluding collection of usable data as per visual inspection and session notes). For dyads without successful completion all contexts, the reasons for missing data are provided (Table 3). Secondly, for a subset of 147 contexts for which data processing is currently complete, the percentage of clean epochs after artifact rejection are reported across timepoint and context (Table 4). Finally, for these 147 contexts, the number of epochs in each engagement state of interest after artifact rejection is reported (Table 4).

Methods

Participants

Participants analyzed here were 186 toddlers and their parents who were part of a larger longitudinal study, The When to Worry Study, focused on earlier identification of mental health and language disorder risk (e.g., Manning et al., 2020). Participants were recruited from pediatric clinics in the greater Chicago area, through community locations and events, and through social media. Participants are followed longitudinally and complete surveys at home via online questionnaire, assessments via videochat, as well as yearly lab visits for behavioral/observation measures and EEG. Exclusion criteria included a child with a diagnosed developmental disability, major developmental delay or medical diagnosis (e.g., epilepsy) or parent lacking language proficiency to complete study measures in English. The sample was enriched for children with higher levels of irritability and who were late talkers (defined as age 19-26 months with vocabulary size below 15th percentile for age and sex on the MCDI, or not yet combining words). Late-talking children also met criteria of hearing English at least 80% of the time at home. Parental informed consent was obtained and families were compensated for their time. All procedures were approved by Northwestern University's Institutional Review Board.

Timepoints and Data Selection

Study data collection is ongoing. EEG data were collected from 186 toddlers aged 24–47 months and their parent at two timepoints, at age 2 and age 3; five participants at the age 2 time point had two EEG attempts in order to get complete EEG data, and 25 of these participants completed both age 2 and age 3 timepoints. To date, 180 sessions for the age 2 timepoint and 31 sessions for the age 3 timepoint have been collected (*n* = 216 unique sessions). Demographic characteristics of the participants at each timepoint are given in Table 1. To examine how much clean data remained after artifact correction, data from 147 successful contexts which have been processed to date we examined. It is important to note that these contexts were from successful sessions (participants were successfully capped and completed all contexts).

Data Collection

Toddlers and their parents completed the Social EEG paradigm as described above. Data collection occurred at the end of the lab visit, after approximately 2-3 hours of other developmental assessments. (Visit order considered the gel-based system used for EEG, so that children and their parents did not need to complete the rest of the visit gel in their hair.) EEG was recorded using two, linked BioSemi ActiveTwo Systems (BioSemi B.V., Amsterdam). Active Ag-AgCl electrodes were affixed to an elastic cap appropriate for the child and parent's head sizes (Electro-Cap Inc., Eaton, OH) that was secured with a fabric strap under the chin. EEG was recorded from 32 scalp sites from each participant. The parent was additionally fitted with external vertical and horizontal eye electrodes and right and left mastoid electrodes; very few children in our pilot data tolerated placement of these electrodes, so they were not used for this study. BioSemi recordings are made in single-ended mode that amplifies the difference between each electrode site and a common mode sensor (CMS) electrode with referencing off-line. The impedance does not need to be lowered with this system due to the combination of pre-amplifiers at each electrode site, a driven right leg (DRL) circuit, and high electrical isolation (Kappenman & Luck, 2010). Offset values were kept below 40 mV during recording. 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.

EEG Preprocessing, Event Merging, Artifact Correction, and Artifact Rejection

Data were processed using EEGLab 14.1.1 and ERPLab 7.0.0 software packages running in MATLAB R2019b. Data were imported, referenced to electrode Cz, and high-pass filtered at 0.1 Hz (half-power cutoff). Channels with consistently poor connection or excessive artifacts were interpolated with the average of surrounding channels using the spherical interpolation function in EEGLab (Delorme & Makeig, 2004); this approach was used sparingly to preserve the most data possible. The list of event codes corresponding to the behavioral microcoding was merged with the list of event codes corresponding to the EEG data (based on the event codes existing in the file for the starting of recording and every elapsed minute). This merged eventlist was then imported into the continuous EEG data file. Data were then separated into 1 second epochs; the first 500 ms of each interval as well as any remaining time after the 1-second epochs fit in to the interval was discarded (Figure 2). Thus, for example, an instance of joint engagement behavior that lasted 25.8 seconds may result in a series of epochs as follows: 6 clean epochs, 4 artifact epochs, 10 clean epochs, and 5 artifact epochs. Thus, the longest segment of continuous EEG from this one behavior code would be 10 seconds. In theory, the shortest contiguous segment in a given instance of a state could be just 1 second (though behavioral codes lasted at least 2 seconds).

Eye blinks and horizontal eye movement artifacts were identified and corrected using independent component analysis and the linear trend variance tool in EEGLab. The moving window peak-to-peak function in ERPLab (Lopez-Calderon & Luck, 2014) and the linear trend/variance function in EEGLab were used to reject remaining trials with artifact (including muscle activity and head/body motion). The moving window peak-to-peak function was most effective for detecting and rejecting sharp artifacts, and the linear trend/variance function was most effective for detecting and rejecting drift when needed. Thresholds were set and accuracy of artifact rejection was visually confirmed for each subject (Luck, 2014). The main moving window peak-to-peak threshold used ranged from 130-180 mV for the child data and 100-160 for the parent data.

Results

Child and Parent EEG Success Rates from Social EEG

We first assessed success rates across the Social EEG contexts, which was defined as a dyad who was able to be successfully capped and completed all 4 contexts without excessive movement or fatigue affecting the data (per visual inspection). Based on our pilot work, these successful sessions are anticipated to result in at least 30 artifact-free, 1-second epochs per condition, which is a common minimum amount of data in previous studies to ensure reliability (McEvoy et al., 2015; Salinsky et al., 1991). EEG files not considered usable at the time of data collection (due to capping trouble, excessive movement, etc.) will not be further processed. A high percent of individuals, 84% of children and 82% of parents, had a successful Movie context, which is most similar to typical resting state or baseline EEG paradigms. Furthermore, 83% of children and 81% of parents had a successful movie context and at least one social interaction context (i.e., Puzzles or Books), which allows for comparison of naturalistic social interaction to baseline movie-watching akin to previous studies of manipulated social contexts. Finally, data quality was good across all 4 contexts, 72% of dyads successfully completed all 4 contexts with usable data for both parent and child. Overall, this feasibility data indicates successful rates for comparing conditions of interest. To obtain these data, some contexts were repeated (see Table 3). At age 2, 9.7% of contexts overall were repeated (17.4% of movie, 8.6% of puzzle, 4.3% of book, and 7.2% of form). At age 3 (fewer sessions complete overall to date), 13.9% of contexts were repeated (26.2% of movie, 18.4% of puzzle, 3.1% of book, and 3.1% of form).

We also examined reasons for unsuccessful sessions. The most common reasons a child did not provide data for all contexts were removal of the cap (8.8%) or excessive movement during EEG (6.9%). In 2.7% of cases, the parent declined to complete the EEG part of the study, often due to time constraints. The most common reason a parent did not have a successful session was due to having a wig or hair extensions incompatible with the cap (3.2%) or trouble getting a connection, often because of amount or thickness of hair (3.2%), thus the initial *n* for children's data is higher than the initial *n* for parents' data. If the child could be capped but the parent could not (e.g., due to hairstyle), the EEG data collection session continued and only child data were collected. If child could not be capped but the parent could (e.g., due to child behavior), we did not continue the EEG session.

Preliminary Rates of Usable Epochs after Artifact Rejection per Context and Timepoint

The percentage of usable epochs after event-merging and artifact correction and rejection is reported in Table 4 for a subset of 147 contexts in which data have been fully processed. These data do not fully represent the data collected to date, as they are a small subset drawn from dyads with successful sessions (as defined above) for preliminary analyses; data from dyads who could not successfully complete the EEG paradigm were not further processed. Each context yielded a large number of usable epochs for both the child and parent, on average more than 50% of data collected, and even more usable epochs when only data from the child was considered (as this can be analyzed on its own, as well). The paradigm was the same at both timepoints, but the mean number of usable epochs per context was higher for 3-year-olds (268 usable child epochs, 218 usable child and parent epochs) than 2-year-olds (219 usable child epochs, 160 usable child and parent epochs).

Preliminary Rates of Usable Epochs per Engagement Code

Lastly, we also examined the number of usable parent and child epochs after artifact rejection in the engagement codes of interest for each context. This is important because each context is designed to elicit varied codes, and we require at least 30 usable epochs per condition for analysis based on previous literature (McEvoy et al., 2015; Salinsky et al., 1991). Overall, there were sufficient usable epochs needed to examine engagement codes either within a single context or by combining across multiple contexts depending on research questions of interest (Table 4). On average, the Puzzles and Books contexts each yielded approximately 150 usable parent and child epochs coded as person engagement/joint engagement. There were, on average, 150 usable parallel object engagement epochs in the Movie context and 132 separate object engagement epochs in the Movie and Forms context.

Discussion

Here, we described the rationale for studying the developing brain using methods that are naturalistic and reflect the real-world situations that children experience. We described a novel Social EEG paradigm that allows examination of naturally occurring parent-child interactions formative for early cognitive, social, and language development. Finally, we provided initial feasibility data from an ongoing study of toddlers and their parents relative to the Social EEG paradigm.

A large proportion of participating toddlers and parents successfully completed our naturalistic Social EEG paradigm, and preliminary analyses indicate that this paradigm yields high rates of usable epochs, even with relatively strict artifact detection procedures employed. Previous work has demonstrated attrition rates for EEG studies as high as 30% - 45% in toddlers age 2-3 years (Bell & Cuevas, 2012). Successful EEG data collection in toddlers can be especially difficult as children must be tolerant of cap fitting, electrode application, and become relatively habituated to the cap in order to sit still during data collection. Our rate of successful child EEG recordings (84% of children) for the movie context, which is most similar to typical resting state or baseline EEG paradigms, is highly comparable with a previous study showing that approximately 85% of 3-year-olds are successful (have more than 25% of data included from a 6-7-minute recording) while the child watched a movie (van der Velde & Junge, 2020).

Notably, the vast majority of the children in our sample completed the EEG at the end of behavioral assessment visit lasting over 2 hours. Our study's use of engaging, naturalistic tasks, as well as relatively long intervals of data collection per context are helpful in avoiding the challenges that some other studies face, such as children being able to understand and willing to follow task instructions and looking at a certain person or screen. We also suggest that the toddler being able to see their parent as a model as the parent wore the EEG cap may have encouraged some children who would be hesitant or unhappy about wearing the cap to complete the session. There are some additional factors that may account for the fact that about 15% of children did not successfully complete the paradigm due to removing the cap or becoming too frustrated to continue. We had a higher rate of irritable children in this sample by design, and previous work indicates that children with negative temperament are less likely to complete an EEG paradigm (Marshall et al., 2009).

Considerations and Limitations of Social EEG

Despite the advantages of the Social EEG approach, there are some notable limitations. Because our goal was to capture neural correlates of naturalistic parent-toddler interaction via behaviorally defined states such as joint engagement, we used a gold-standard behavioral coding scheme, adapted for engagement state between the parent and child. This method can be more time-consuming in terms of coding and processing that traditional baseline or passive-viewing paradigms. Indeed, any type of detailed coding can be time-consuming. After this initial validation and for those interested in other research questions, future work could consider if similar information could be obtained by more streamlined coding or global measures such as a rating scale. We felt that starting with an established and detailed coding scheme was the best way to start on applying coding to interactions during EEG.

In order to maximize our ability to capture behaviors of interest during naturalistic interactions, we did not present standardized stimuli and instead used the state-based coding to identify moments of interest from natural interaction. This has many advantages including capturing more true-to-life behavior, but inevitably also reflects some variability (differences among movie choice, puzzle choice, book choice, etc.); however, the behaviors or states of interest (e.g., joint engagement, object engagement) are precisely defined and the focus of analytic comparisons. This is a markedly different approach than many studies which closely control stimuli but do not code for behavioral engagement. Beyond the rationale of aligning with our study aims, this approach also has the methodological advantage of being more feasible for young children and children with disabilities to complete. This “baseline” in some ways aligns with previous studies that aimed to have a relatively neutral context for comparison to other states or stimuli, but because we are not focused on comparing baseline across children, it also differs. Overall, it is important that researchers consider that there may be more differences than similarities across resting paradigms (Camacho et al., 2020).

Processing dyadic EEG data requires artifact correction and rejection from two participants, which requires adaptation of EEG processing pipelines and consideration of new factors. Though our design employing the various contexts seems to provide sufficient numbers of clean epochs within each code for analysis (Table 4), there are some new analytic considerations for this paradigm in which events of interest (given instances of a behavior code) vary in length. We selected a minimum state duration of 2 seconds for the behavior coding, consistent with existing behavioral coding schemes; however, within an instance of a given code, the duration of the code can be interrupted by artifacts, creating varying numbers of consecutive usable 1-second epochs within a state. Our current EEG processing pipeline utilizes ICA to correct common artifacts (e.g., eye blinks) in order to retain as much usable data as possible. We are currently also examining processing pipelines developed for child data (e.g., Debnath et al., 2020; Gabard-Durnham et al., 2018) that use more extensive artifact correction in order to retain larger segments of continuous EEG data which may be optimal for more complex parent-child synchrony analyses. The optimal number of consecutive events for EEG analysis is not yet clear; future studies may examine stability or reliability of EEG measures in relation to these indices.

Fitting toddlers and parents with caps simultaneously is challenging and requires trained research assistants familiar with working with children. Furthermore, one broad consideration with EEG is the need for cap fitting, which is more difficult when participants have very thick or curly hair, wigs, or hair extensions; these difficulties are noted in our usability data. The challenges unfortunately limit our ability to obtain data from some families, more often with Black/African American families; this is a frequent and important consideration across EEG research (Choy et al., 2021). We work with families as much as possible to schedule visits around times when getting gel in their hair is less inconvenient (such as right before their hair is scheduled to be braided or rebraided, etc.) or only collecting child EEG or only other study measures.

Clinical Relevance

More interactive and naturalistic EEG paradigms with fewer instructions and restrictions (i.e., not requiring that the child sit as still and watch stimuli on a screen) and a more engaging task, such as free play with a parent, could alleviate some of the challenges that arise when collecting brain data from toddlers. This is especially important for children that may need additional support during EEG data collection, such as children with sensory sensitivities (e.g., children with autism), or those who have difficulty following task instructions, including children with limited verbal and/or cognitive abilities. In the future, if naturalistic EEG markers can be identified that correspond to complex social behaviors, these markers may help to identify which children may go on to develop disorders and who may most benefit from early intervention (Dawson et al., 2012; Jeste et al., 2015). Interpersonal synchrony is also a major area of interest for researchers studying autism, which is characterized by difficulties with social communication (McNaughton & Redcay, 2020; Rolison et al., 2015) in diagnosed individuals and family members (Nayar et al., 2018). The present paradigm has the advantage of simultaneously capturing parent and toddler behavior, which can provide crucial information for tailoring interventions, such as whether some social skills or sensitivities may be present in the absence of overt behaviors. Because children are assessed and receive treatment for various developmental disorders including autism, language disorders, and mental health conditions in naturalistic, interactive contexts with an adult, understanding how the brain functions in these dyadic interactions may inform clinical assessment and practice. Adaptations for clinical feasibility will be an important aspect of pragmatic refinement.

Future Directions

Our next step is to assess the degree to which our behavioral codes reflecting engagement state align with well-validated patterns from more structured studies, for example, the finding that alpha power suppression is associated with increased attention (Perry et al., 2011), and if examining neural markers of joint engagement as defined by the behavioral literature gives us a more detailed look at these constructs. Subsequent planned work will examine EEG metrics of child engagement with their parent (e.g., alpha, mu, and theta power during joint engagement vs. separate object engagement), as well as parent-child neural synchrony, and how these indices may relate to child growth in language, cognition, and socio-emotional skills. We hypothesize that strong parent-child neural synchrony may support development, and perhaps serve as a protective factor for children who have high irritability or who have delayed language.

Another dimension to consider is affect and irritability in relation to socio-emotional development. For each instance of a state, we also have sub-codes for frustration and affect (negative, positive, neutral). Analyzing these data may allow additional comparisons with existing paradigms. We also have collected an additional, experimental context of frustration induction; in this context, the experimenter shows the dyad an enticing toy, a child-friendly tablet. The tablet has a small hidden switch that allows it to be turned off, before it is handed to the child. The non-functioning tablet is given to the child, and then multiple rounds of handing it back to the experimenter (who flips the switch and shows it to be working), and back to the child, are completed. We plan to analyze this task in the future.

One of our fundamental questions is how joint engagement is related to parent-child neural synchrony; certainly, a dyad who appears more “in sync” may demonstrate similarities on a neural level. However, we must also take into consideration that shared sensory input alone may be reflected in the brain. We have designed the movie and the movie and forms contexts to tease apart moments when a dyad is not interacting but sharing a stimulus (audio and video from the movie) and when they are neither interacting nor sharing a visual stimulus. These data could help answer how much inter-brain synchrony is really explained by shared joint engagement, as opposed to the overlap in processing the same sensory stimuli.

There are multiple measures for assessing neural synchrony; power similarity is one way (Bowyer, 2016). Phase synchrony within a given power band is another measure of inter-brain synchrony. Because phase synchrony is meaningfully compared only within the same frequency band, this can be challenging for parent-child studies in which the frequency band shifts over development. For example, with the alpha band defined as 6-9 Hz in children and 8-13 Hz in adults, phase synchrony could be compared at 8 Hz. There are yet other measures related to coherence, and even Granger causality, which can be used to infer causal relations between one person and the other (e.g., Wass et al., 2018).

Future studies should consider assessing various other dimensions of caregiver-child interactions. For example, including fathers in studies of parent-child interactions would be informative, especially when interested in inter-brain synchrony and potential genetic influences between parent and child neurobiology, as paternal and maternal effects may differentially affect child outcomes (Riva et al., 2019). The flexibility and naturalness of the Social EEG paradigm mean that the myriad factors that may affect the behavioral manifestation of caregiver-child interaction, such as culture, child age, and family risk and protective factors (stress, depression, warmth, responsiveness), and many more, could be examined (Morris et al., 2020).

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Table 1

Demographic Characteristics of Toddlers and Their Parents for Social EEG Sessions Collected to Date, by Timepoint

	Year 2		*Year 3*	
	Toddlers	*Parents*	*Toddlers*	*Parents*
Number of participants	180	180	31	31
Age (mean ± SD)	26.9 ± 1.7 months	34.9 ± 4.7 years	40.3 ± 2.1 months	34.4 ± 7.2 years
Age range	24-32 months	22-46 years	35-45 months	20-43 years
Sex (% female)	32.4%	99.4%	35.5%	96.8%
Income-to-needs ratio		5.6 ± 6.0		6.2 ± 10.1
Race				
Asian	1.1%	3.3%	0.0%	3.2%
Black/African American	16.7%	16.7%	22.6%	22.6%
Native Hawaiian/ Pacific Islander	0.0%	1.1%	0.0%	0.0%
White/Caucasian	67.8%	71.7%	61.3%	67.7%
More than one race	10.0%	0.6%	9.7%	3.2%
Unknown/not reported	4.4%	6.7%	6.5%	3.2%
Ethnicity				
Hispanic/Latino	11.1%	8.3%	6.5%	3.2%
Not Hispanic/Latino	88.9%	90.0%	90.3%	93.5%
Unknown/not reported	0.0%	1.7%	3.2%	3.2%

Notes: Income-to-needs ratio is the ratio of the family's household income to the US census income cutoff for poverty, based on household size. Not all percentages for race sum exactly to 100% due to rounding. Data represents the 186 unique participants; some have completed both visits, so they are counted at both Year 2 and Year 3 timepoints in this table but only once in the overall n=186.

Table 2

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

Code	Description	Example
Coordinated Joint Engagement	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	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	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	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	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.

Table 3

Data Usability and Reasons for EEG Data Loss for All Sessions (n = 216)

	n	%
Session usable	156	72.0%
EEG not attempted due to time constraint or parent declining	6	2.8%
Child refused cap, gelling, or could not sit in chair	8	3.7%
Parent could not be capped due to wig or hair extensions	7	3.2%
Could not get usable connection with child scalp	0	0%
Could not get usable connection with parent scalp	7	3.2%
Extremely poor data quality and/or discontinued contexts due to child movement, fatigue, etc.	15	6.9%
Extremely poor data quality due to parent movement, fatigue, etc.	3	1.4%
Child removed cap during session	19	8.8%

Notes: Some sessions had more than one reason that data were unusable, so percentages sum to more than 100%. Data is considered per dyad across all four contexts. This table represents all 186 participants' EEG sessions, across one (Year 2 or Year 3) or both (Year 2 and Year 3) timepoints, resulting in 216 total sessions counted.

Table 4

Number of Usable 1-second Epochs for Child Data and Combined Parent and Child Data by Context, and Engagement Code (n = 147 processed contexts)

		# of Total Usable Epochs Mean (SD)		# of Usable Epochs by Code Mean (SD)		
		Child Only	Parent and Child	Parent and Child		
				Person/Joint Engagement	Parallel Object Engagement	Separate Object Engagement
Context	*n*					
Movie	48	200 (79)	173 (77)	4 (9)	**150 (70)**	1 (4)
Puzzles	27	252 (103)	172 (102)	**151 (90)**	0 (0)	3 (14)
Books	44	259 (93)	170 (87)	**154 (90)**	0 (2)	2 (9)
Movie and Forms	28	213 (68)	174 (66)	0 (2)	20 (29)	**132 (70)**

Notes: This table represents usable epochs for a subset of *n*=147 total successful contexts which have been coded, processed, and artifact-rejected. Usable parent and child epochs are also reported for engagement codes of interest in each context. The code that each context was designed to elicit is in bold font.

Figure 1. Photo of Social EEG paradigm setup.

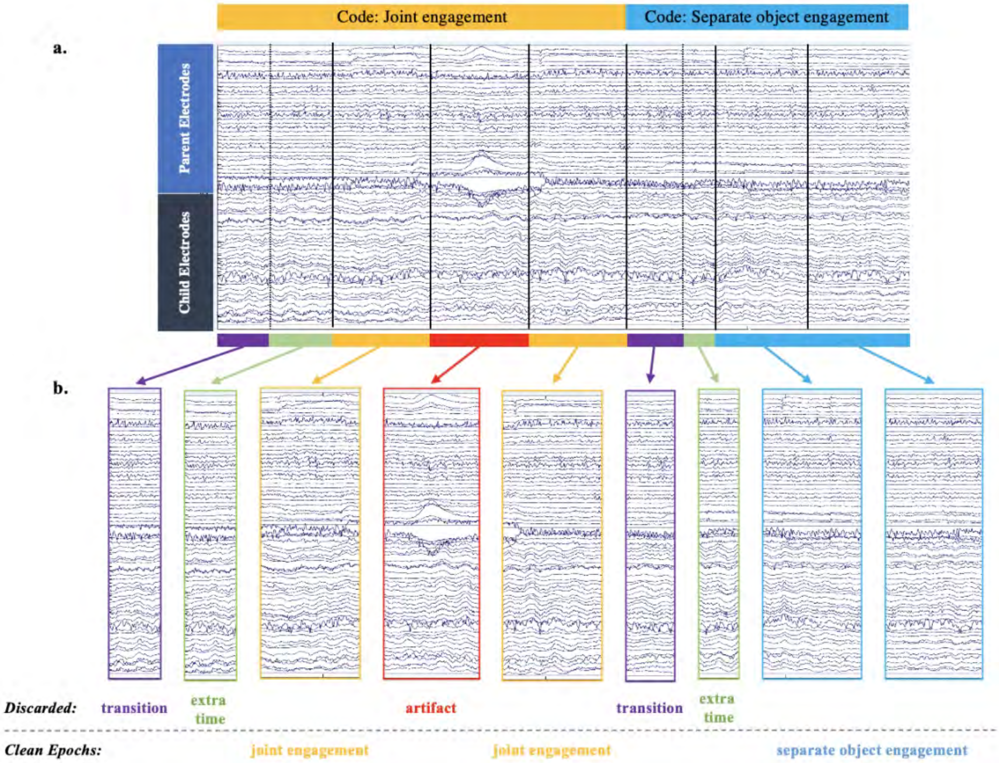

Figure 2. Schematic of EEG data events and separation by code. a. Continuous EEG data (5 sec of continuous data) with parent electrodes on top and child electrodes on the bottom. Event markers for onset of events and 1-second epochs are indicated by vertical lines. b. Demonstration of how the EEG time series data is separated into data that are used for analysis or excluded. Event codes (solid lines) corresponding to onset of a new behavioral state are added to the EEG file, in order to create 1-second epochs. A 500ms transition period (onset indicated by dotted line) is excluded, as is the extra time that does not fit cleanly into 1-second epochs. Epochs with remaining artifacts are then rejected, leaving only artifact-free epochs.