Cognition 214 (2021) 104752

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Neural synchrony predicts children's learning of novel words

Elise A. Piazza [a,b,c,*], Ariella Cohen [b,d], Juliana Trach [a,e], Casey Lew-Williams [a]

[a] Department of Psychology, Princeton University, United States
[b] Princeton Neuroscience Institute, Princeton University, United States
[c] Department of Brain & Cognitive Sciences, University of Rochester, United States
[d] Icahn School of Medicine at Mount Sinai, United States
[e] Department of Psychology, Yale University, United States

ARTICLE INFO

Keywords:
Word learning
Book reading
Neural synchrony
fNIRS

ABSTRACT

Social interactions, such as joint book reading, have a well-studied influence on early development and language learning. Recent work has begun to investigate the neural mechanisms that underlie shared representations of input, documenting neural synchrony (measured using intersubject temporal correlations of neural activity) between individuals exposed to the same stimulus. Neural synchrony has been found to predict the quality of engagement with a stimulus and with communicative cues, but studies have yet to address how neural synchrony among children may relate to real-time learning. Using functional near-infrared spectroscopy (fNIRS), we recorded the neural activity of 45 children (3.5–4.5 years) during joint book reading with an adult experimenter. The custom children's book contained four novel words and objects embedded in an unfolding story, as well as a range of narrative details about object functions and character roles. We observed synchronized neural activity between child participants during book reading and found a positive correlation between learning and inter-subject neural synchronization in parietal cortex, an area implicated in narrative-level processing in adult research. Our findings suggest that signature patterns of neural engagement with the dynamics of stories facilitate children's learning.

1. Introduction

Social interaction and communication are central in facilitating children's early learning. Language learning, including the acquisition of lexical, syntactic, and pragmatic knowledge, is highly dependent on social engagement with adults and other children, which helps guide learners' attention toward the most useful input (Tomasello, 1992). A myriad of multimodal parental behaviors, including speaking about and touching objects, extend the duration of infant attention (Suarez-Rivera, Smith, & Yu, 2019) and may contribute to children's self-regulation of attention across many interactions (Kopp, 1982; Miller, Ables, King, & West, 2009; Vygotsky, 1978). While recent work has begun to characterize the neural correlates of social communication in adults (Silbert, Honey, Simony, Poeppel, & Hasson, 2014; Stephens, Silbert, & Hasson, 2010), the neural mechanisms underlying learning and social engagement in young children are largely unknown. In this study, we recorded activity from children's brains while they engaged in natural, joint book reading with an adult to investigate the neural mechanisms underlying learning during social communication. We focused in particular on children's learning of novel words embedded in a storybook.

If the primary function of language is to communicate ideas and intentions to others, it is therefore unsurprising that language learning relies on communicative contexts – an idea that has been investigated in a wealth of previous research. For example, in one study, infants learned sound categories better from in-person interactions than from audio or audiovisual recordings (Kuhl, Tsao, & Liu, 2003), and in another, infants only succeeded in learning a pattern embedded in a novel auditory signal if it was presented in a communicative context (Ferguson & Lew-Williams, 2016). In addition, contingent social feedback from caregivers, including smiling, touching, and vocalizing, has been shown to shape the acoustic features of infants' babbling (Goldstein, King, & West, 2003; Goldstein & Schwade, 2008). The ability to engage in joint attention with adults emerges early in development and predicts children's later vocabulary size and their learning about novel objects (Mundy et al., 2007; Striano, Chen, Cleveland, & Bradshaw, 2006). These findings, among many others, converge to suggest that social interaction plays an important role in early language learning.

If joint understanding and learning develop through social

* Corresponding author at: Department of Psychology, Princeton University, United States.
E-mail address: elise.piazza@gmail.com (E.A. Piazza).

https://doi.org/10.1016/j.cognition.2021.104752
Received 28 July 2020; Received in revised form 21 April 2021; Accepted 26 April 2021

interactions, what are the neural mechanisms that support this transfer of representations? Recent neuroimaging work, primarily with adult participants, has begun to investigate the neural mechanisms that underlie individuals' representations of shared input. Some of this work has focused on listener-listener neural synchrony, and other work has focused on speaker-listener neural synchrony (i.e., coupling). Regarding the former, a number of functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIRS) studies have found that adults' brains exhibit synchronized activity when exposed to the same video or audio recording (Hasson, Nir, Levy, Fuhrmann, & Malach, 2004; Liu et al., 2017; Wilson, Molnar-Szakacs, & Iacoboni, 2008). These studies have used intersubject correlation (ISC), a measure of synchrony between the neural signals of multiple individuals, to quantify how similarly the dynamics of external input are represented across different observers' brains. ISC reduces individual-specific noise and isolates a stimulus-driven neural signature that is consistent across subjects, therefore revealing shared responses to the moment-to-moment dynamics of rich, naturalistic stimuli.

Importantly, converging evidence has demonstrated that neural synchrony depends not only on exposure to the same stimulus, but also on a partially or even fully shared high-level understanding of its meaning. For example, significant listener-listener synchrony has been observed not only in areas associated with low-level auditory processing (primary auditory cortex), language production (inferior frontal gyrus), and speech comprehension (superior temporal gyrus and temporo-parietal junction), but also in higher-order, extralinguistic, default mode network (DMN) regions, including the precuneus, parietal lobule, intraparietal sulcus, medial prefrontal cortex, and dorsolateral prefrontal cortex (Yeshurun, Nguyen, & Hasson, 2021). These higher-order regions are associated with processing of social information (Iacoboni et al., 2004) and long-timescale narrative structure (Lerner, Honey, Silbert, & Hasson, 2011). Furthermore, synchrony in these regions while listening to natural stories is thought to reflect a joint understanding of high-level narrative information, rather than mere exposure to shared input. When adults hear nonsense speech, scrambled speech, or a narrative spoken in a foreign language, synchronization between their brains disappears except in primary auditory cortex (Honey, Thompson, Lerner, & Hasson, 2012; Liu et al., 2017; Silbert et al., 2014). Rather than reflecting an epiphenomenon, neural synchrony may play an active role in learning. During natural interactions, important features of communicative input (e.g., adult behaviors, or structural elements of a story narrative) may serve to nudge a child learner's brain into a transient state of phase entrainment, such that it becomes maximally excitable during optimal moments for encoding information (Wass, Whitehorn, Haresign, Phillips, & Leong, 2020).

While research on listener-listener synchrony has revealed signature ways of engaging with input, speaker-listener synchrony, or coupling, can reveal how information is transferred between people producing and comprehending speech. Several studies have investigated this form of transfer by measuring coupling between the brain of a speaker telling a personal story and, later, in a separate session, of participants listening to a recording of the story (Liu et al., 2017; Stephens et al., 2010). In contrast to these studies, which measured speakers' and listeners' responses in separate sessions, a recent study measured speaker-listener (adult-infant) coupling in the context of live, face-to-face interactions (playing, singing, and reading), finding that the prefrontal cortex showed the strongest coupling, as well as a relationship to several communicative behaviors including mutual gaze, joint attention to objects, infant emotion, and infant-directed speech (Piazza, Hasenfratz, Hasson, & Lew-Williams, 2020). Related work has shown stronger adult-child coupling when the members of a dyad solve a problem cooperatively vs. separately (Nguyen et al., 2020).

Given the emerging understanding of brain-to-brain synchrony between people, the next vital question is how it contributes to the real-life goals of communication, such as learning. In particular, is the degree of neural synchrony between a child learner and other young learners predictive of the child's learning? While previous experiments (e.g., Stephens et al., 2010) have largely investigated overall comprehension of a recorded narrative as a measure of the quality of intersubject communication, the present study assessed the correlation between brain-to-brain synchrony and fine-grained word learning from a storybook. Joint book reading in early childhood – a social experience shared by children and caregivers around the world – has been linked to long-term language outcomes, including vocabulary size and literacy (Bus, van IJzendoorn, & Pellegrini, 1995; Dickinson, Griffith, Golinkoff, & Hirsh-Pasek, 2012; Dowdall et al., 2020; Noble et al., 2019). We created an original, multifaceted children's book that enabled analysis of learning at multiple levels, including novel word learning, understanding of object functions, and broader narrative comprehension. In each session, a live experimenter read the story aloud to the child participant. Although the book was presented digitally in order to enable temporal alignment of story events with the neural signals, it was otherwise the same as a traditional book. The book did not include electronic features that characterize some tablet-based e-books for children, such as dynamic animations, audio narration, or touch sensitivity (see Parish-Morris, Mahajan, Hirsh-Pasek, Golinkoff, & Collins, 2013; Reich, Yau, & Warschauer, 2016). Our joint book reading paradigm thus both afforded temporal control over stimulus presentation and served as a naturalistic context for communication.

To investigate the neural underpinnings of learning from a storybook in preschool-aged children, we used functional near-infrared spectroscopy (fNIRS) to record the neural activity of child participants during joint book reading with an adult experimenter. fNIRS is a neuroimaging modality that uses near-infrared light to record changes in the concentrations of oxygenated and deoxygenated hemoglobin to approximate neural activity. fNIRS is minimally sensitive to motion, which, in addition to permitting naturalistic, reciprocal, real-time interaction, makes it ideal for studies involving children. Following the storybook, we assessed the children's word learning and story comprehension. Although we intended to examine both listener-listener synchrony and speaker-listener synchrony, the quality of the adult signal unexpectedly declined over the course of data collection (see Method and Supplementary Fig. 1), so we were unable to meaningfully analyze speaker-listener synchrony with sufficient data or confidence. We will henceforth focus on listener-listener synchrony.

Building on previous studies reporting shared neural representations of stimuli between adult listeners (Honey et al., 2012; Liu et al., 2017; Yeshurun et al., 2017), we expected that while listening to a story, neural synchrony between child participants, particularly in prefrontal and parietal cortices, would predict learning. If an individual child's neural signature is closer to an overall stimulus-driven pattern, one might expect the child to more effectively extract structure and learn; conversely, if an individual child's neural signature is less similar to the group as a whole, one might expect the child to show either reduced learning or idiosyncratic patterns of learning. Therefore, we anticipated that children whose patterns of neural activity were more (versus less) synchronized with those of other participants would show increased learning of words and other story details. If child-child neural synchrony does predict successful learning, this would enhance our understanding of how the brain engages with the moment-to-moment dynamics of linguistic and social input.

2. Method

2.1. Participants

Sixty-nine children aged 3.5–4.5 years old (M = 47.0 months; SD = 3.55 months; 33 females) participated in the study. The majority of participants were white and had parents with a college degree (or higher), and the sample reflected the demographics of the Princeton University community, both in race and socioeconomic status. All children were born full-term, had no history of hearing problems or known developmental delays, and were raised in English-speaking environments (English spoken at least 85% of the time). One adult female experimenter read the story stimulus to all study participants. Five participants were excluded because they refused or were unable to wear the fNIRS cap, one was excluded for moving the cap during the experiment, one was excluded for poor signal quality. An additional seven participants were excluded due to experimenter error or equipment malfunction, and ten were excluded because of an error in the fNIRS equipment configuration (which nullified the data across ten consecutive sessions). The remaining forty-five participants ($M = 47.5$ months; $SD = 3.68$ months; 19 females) were included in analyses.

2.2. Procedure and stimuli

Each child participant was seated side-by-side with an adult experimenter, who read a custom digital storybook for 4 min and 30 s (Fig. 1). We designed the storybook to expose children to four novel object-label mappings in the context of an engaging narrative (see Fig. 2A and full story on OSF: https://osf.io/cmx8d/). The objects and their labels were selected from the Novel Object and Unusual Name (NOUN) database (Horst & Hout, 2016). The selected objects were highly unlikely to be familiar to participants and had similar visual salience, and their labels (e.g., *foom*, *teebu, glark,* and *koba*) were simple pseudowords, rather than unfamiliar real words, to ensure that participants had no prior exposure to target words. To account for possible subtle differences in label and object salience, children were randomly assigned to see one of two versions of the book; the text was identical in each version, but object-label pairings and order of object presentation were counterbalanced across participants.

The story adhered to a canonical Western plot structure including exposition, conflict, and resolution. Specifically, it followed a simple narrative of an astronaut traveling through space to find four objects that were needed to fix a broken rocket (Fig. 2A). All objects were named three times during the story: once with a colorful backdrop, once in isolation with a black backdrop, and once later in the story with an assigned function (e.g., fixing the engine of the rocket). The story was displayed on a wall-mounted monitor between the child and adult in order to standardize image presentation between the reading and test phases across sessions, and "page-turns" occurred automatically after a predetermined amount of time (approximately 10–15 s per page), which controlled for visual exposure to each object and aligned story events with the neural signals in a consistent way across participants. The text of the story appeared on each page, as in typical storybooks (see Supplementary Information for more details and full story on OSF: https://osf.io/cmx8d/), and the experimenter read the text naturally within the time frame of each page. The timing of each page was determined prior to the initiation of data collection based on how long it took the experimenter to read the text. The experimenter used naturalistic prosody but adhered strictly to the story's text and directed her gaze toward the book, to avoid differences across sessions in the amount of eye contact, nodding, or smiling toward the child. As a result, the adult and child both primarily directed their attention outward toward the story, rather than across at each other. The child participants occasionally smiled, made eye contact, or vocalized. On the rare occasion when a child asked a question, the experimenter briefly acknowledged it with a generic positive response (e.g., "Yeah?") but moved on quickly in order to preserve the timing of each page. This preservation of consistency across sessions was important for our research questions, particularly given the novelty of the experimental paradigm, but leaves an open question about how children learn new information during fully natural interactions.

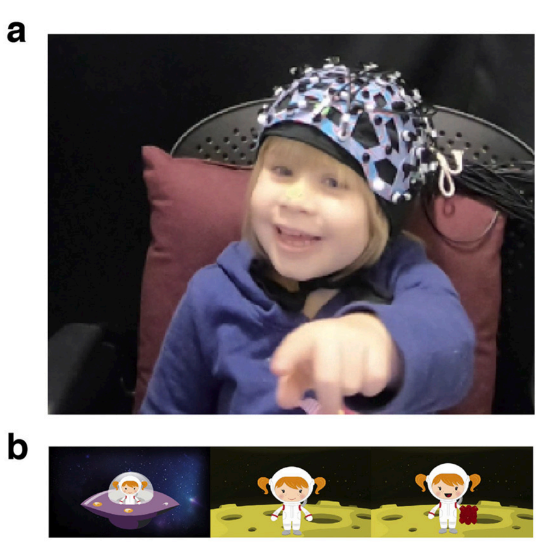

Fig. 1. Experimental setup showing (a) a child participant during book reading and (b) an example excerpt from the storybook. Each page in the story included text in white font (not shown here). The text for these three pages was, respectively, *Sally gets in her spaceship, flies to another planet, and goes to find the last part*; *She gets off her spaceship and looks for one of the missing pieces*; *Sally explores the planet and finds a foom! She likes it.*

2.3. Learning assessment

Following the story, children participated in a two-alternative forced-choice (2AFC) learning assessment to measure their novel word learning and story comprehension (Fig. 2B). Data are available at OSF: https://osf.io/cmx8d/. Each question appeared on the wall-mounted touch screen monitor, and children were asked via prerecorded audio (spoken by the same adult experimenter who read the story) to select one of the two presented images. Questions were designed to assess receptive learning of novel word labels (e.g., *Where is the foom?, Where is the teebu?*), object functions (*Which part did this fix?*), the locations in which events occurred *(Where was Sally when she found the glark?, Where was Sally when she got lost?*), and general story comprehension (*Who helped Sally?*). Participants were asked a total of 31 questions: 16 to assess novel word learning (four questions for each of the four labeled objects) and 15 to assess story comprehension and understanding of object functions (4 function questions, 5 location questions, and 6 general comprehension). The side of target object presentation was counterbalanced to control for possible side bias. Additionally, the order of the questions was inverted for half of the subjects to minimize the effects of distraction or disinterest near the end of the task. We conducted analyses to ensure that there were no effects of object labeling or side bias on performance (see Supplementary Information).

2.4. Neural recording

We recorded children's brain activity during book reading using a LabNIRS system (Shimadzu Scientific Instruments, Columbia, MD). The fNIRS cap covered prefrontal cortex and parts of the temporal and parietal cortex, which have known roles in speech comprehension and social cognition (Wilson et al., 2008). The cap had 20 emitters and detectors, corresponding to a total of 53 channels. We originally planned to measure the neural activity of the adult experimenter, but the quality of the signal from the adult cap declined over the course of data collection (see Supplementary Fig. 1), possibly due to a change in elasticity and resulting fit over time. We attempted to reconstruct a single adult brain template by combining high-quality channels from the adult across sessions, but this proved to be underpowered for comparison to data from each child's brain. Future studies will further explore links between children's learning and real-time neural coupling between children and adults.

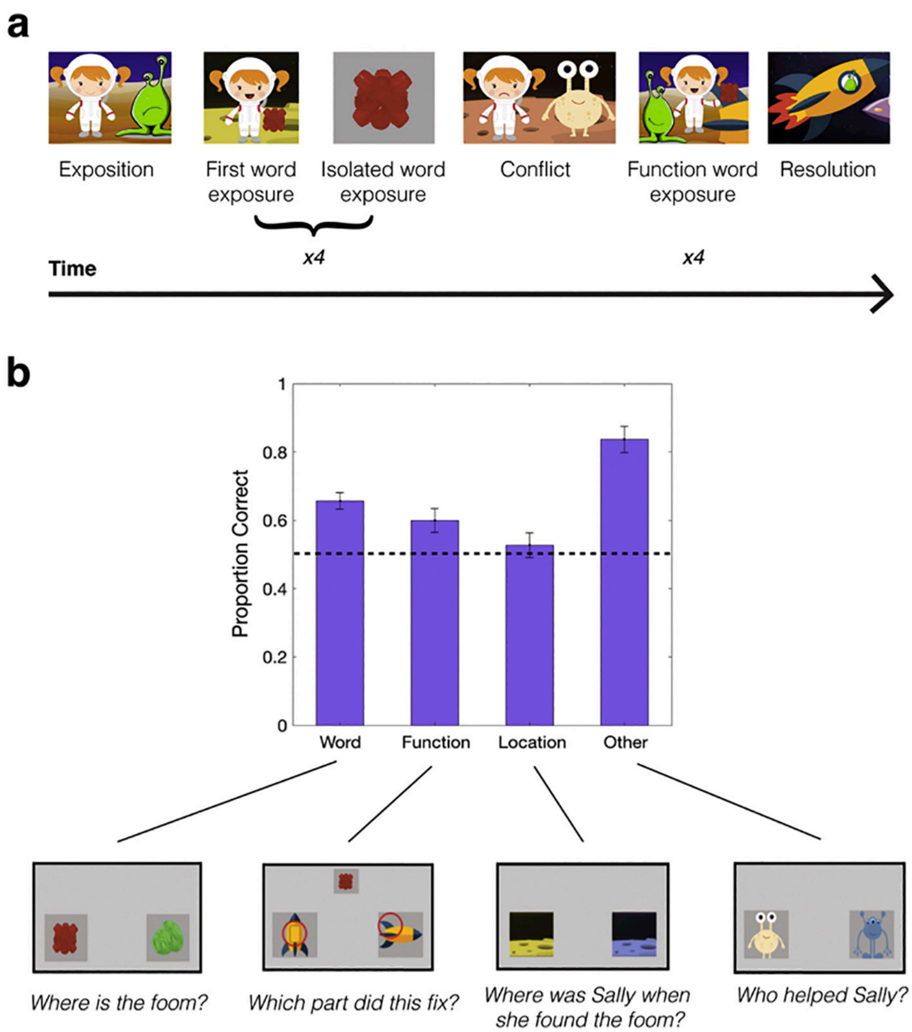

Fig. 2. Story stimulus and learning assessment. (a) Schematic timeline of the storybook, which followed a general Western plot structure including exposition, conflict, and resolution. (b) Learning assessment performance, broken down by question category, with an example question from each category. Questions were presented via prerecorded audio clips spoken by the experimenter.

3. Results

3.1. Data preprocessing and analysis

We conducted analyses to ensure that behavioral results were not biased by order effects, side bias, or object preferences. These analyses (which are described in more detail in the Supplementary Information) resulted in excluding no participants from the main analyses.

We removed motion artifacts using moving standard deviation and spline interpolation (Scholkmann, Spichtig, Muehlemann, & Wolf, 2010) and low-pass-filtered (0.5 Hz) and high-pass filtered (0.02 Hz) the signal to remove physiological noise and signal drift, respectively. To eliminate excessive signal noise, we excluded individual channels in which the time series corresponding to relative concentrations of oxygenated (HbO) and deoxygenated (HbR) were correlated, based on a method established in previous work (Cui, Bray, & Reiss, 2010). We did so because positive correlations between HbO and HbR are likely to be induced by noise, such as head motion artifacts, and it has been widely established that *negative* correlations between them reflect typical neural activation (Cui et al., 2010; Malonek & Grinvald, 1996; Sheth et al., 2004). After z-scoring the signal over the duration of joint book reading, we split the time series (4500 data points) into 45 bins and computed windowed Pearson correlations between the concentration changes for each channel. Channels that showed a positive correlation ($r \geq 0$) between the HbO and HbR concentration changes averaged across all time bins were excluded. For subsequent analyses, we used the relative concentrations of HbO in each channel to calculate neural synchrony, as recent fNIRS research using naturalistic story stimuli found greater correlations between fMRI BOLD response and HbO concentration changes than between the BOLD and HbR signals (Liu et al., 2017). fNIRS data are available at OSF: https://osf.io/cmx8d/.

Analyses included 53 channels from each child's fNIRS cap, grouped into three regions of interest (ROIs): prefrontal cortex (PFC) (7 channels), parietal cortex (22 channels), and bilateral temporal cortex (24 channels). We first averaged the HbO signal (corresponding to the entire time series across the story) across channels within each ROI in a given participant. Then, to compute intersubject correlation (ISC), or the degree of synchrony between the participant and all other child participants, we computed a Pearson correlation between this channel-averaged ROI time series (e.g., prefrontal) for the child participant and the average time series across all other child participants in the corresponding ROI (see Supplementary Fig. 3). The correlations between learning and neural synchrony were computed with a between-subject Pearson correlation between response accuracy and ISC for each ROI.

3.2. Finding 1: preschoolers can learn a range of semantic information from a naturalistic storybook

The story was designed to expose children to semantic information at multiple levels of complexity, from the meanings of individual object labels to higher-order, long-timescale narrative information about character goals and conflict resolution. Using a 2AFC task on a touch screen directly following the story, we measured children's learning of word-object mappings (object labels), the functions of the objects, locations in which the objects were found, and whether certain characters were helpful to the protagonist (Fig. 2B). We found that overall learning (collapsed across all question types) was significantly above chance ($t(44) = 10.6$, $p < .001$, *Cohen's* $d = 1.58$). More specifically, there was significantly above-chance learning for individual object labels ($t(44) = 6.5$, $p < .001$, $d = 0.97$), object functions ($t(44) = 2.86$, $p < .01$, $d = 0.43$), and other general questions about the story (e.g., the names of main characters; which characters helped the protagonist; $t(44) = 16.2$, $p < .001$, $d = 2.42$). However, preschoolers were unable to recall the locations in which individual objects were found ($t(44) = 0.759$, $p = .45$, $d = 0.11$), likely because the locations (planets) were background scenes that only varied by color.

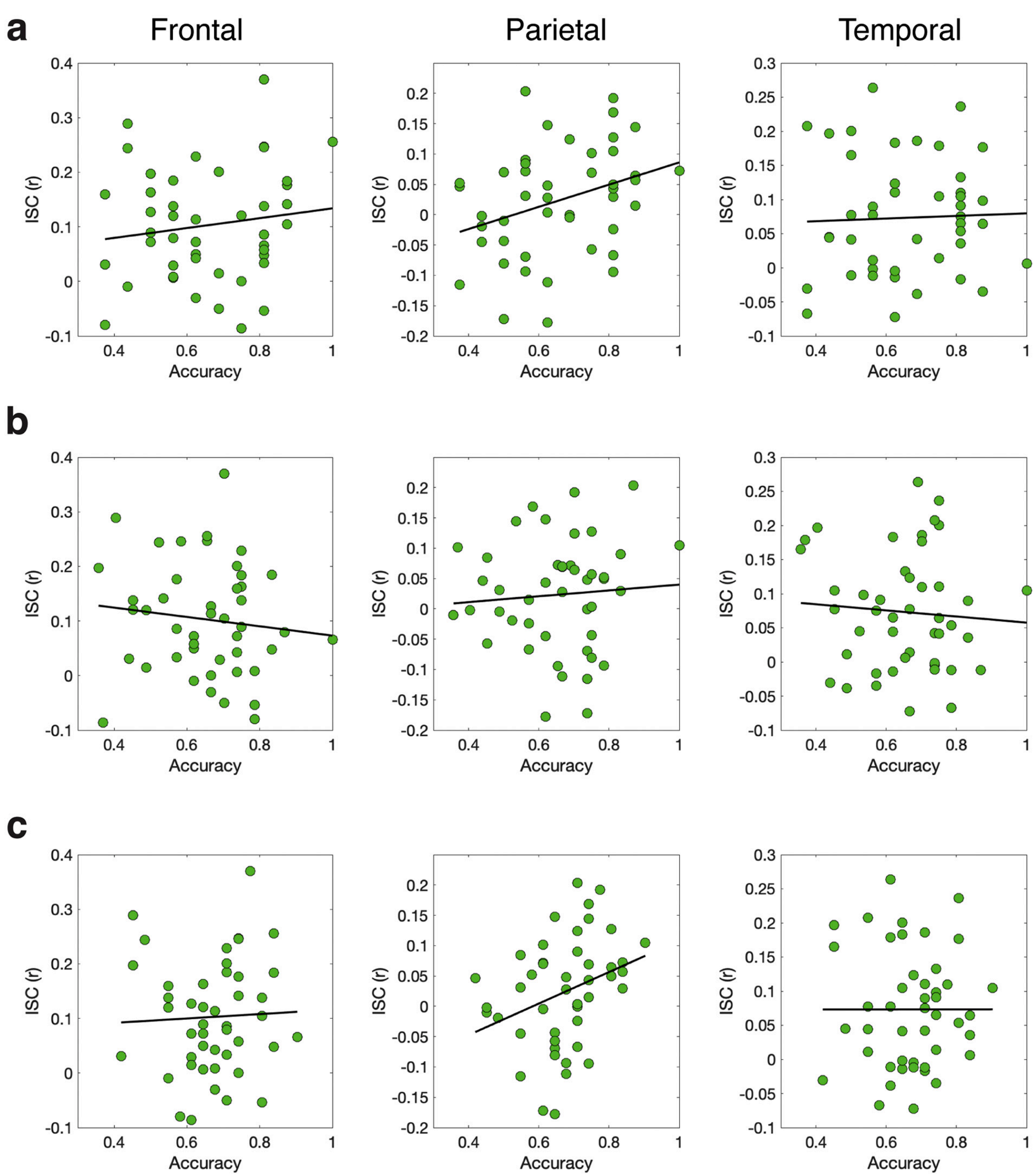

Fig. 3. Relationship between intersubject correlation (ISC) and learning of (a) novel words from the story (object label test questions only), (b) all other (non-word) questions, and (c) overall story content (collapsed across all question categories) in each of 3 neural ROIs. $N = 45$.

3.3. Finding 2: child-child neural synchrony in parietal cortex predicts word learning as well as overall learning across question types

We observed variation in learning both across individual children and across question categories, which enabled us to correlate children's behavioral performance with their neural synchrony.

We iteratively computed the ISC between each child's neural time series across the story and the group-averaged time series across the other 44 participants in each of three cortical ROIs: frontal, parietal, and temporal (see Methods). For each child, we computed the correlation between this ISC value and their learning of novel words from the story (Fig. 3A). This correlation was significant in the parietal ROI ($r(43) = 0.33$, $p < .05$, $R^2 = 0.11$) but not the other two ROIs (frontal: $r(43) = 0.14$, $p = .35$, $R^2 = 0.02$; temporal: $r(43) = 0.04$, $p = .81$, $R^2 = 0.002$). The same pattern was true when we examined the relationship between ISC and overall learning score (accuracy collapsed across all questions; Fig. 3C): parietal ROI ($r(43) = 0.31$, $p < .05$, $R^2 = 0.10$); frontal ROI ($r(43) = 0.04$, $p = .78$, $R^2 = 0.002$; temporal ROI ($r(43) = 0.01$, $p = .99$, $R^2 = 0.001$).

We next looked more closely at the relationship between ISC and learning across other categories of test questions beyond the novel words and their referents. Correlations between ISC and other forms of learning were not statistically significant [Function: frontal ($r(43) = -0.18$, $p = .24$, $R^2 = 0.03$), parietal ($r(43) = -0.08$, $p = .61$, $R^2 = 0.01$), temporal ($r(43) = 0.04$, $p = .81$, $R^2 = 0.002$). Location: frontal ($r(43) = 0.02$, $p = .9$, $R^2 = 0.001$), parietal ($r(43) = 0.07$, $p = .66$, $R^2 = 0.005$), temporal ($r(43) = -0.2$, $p = .19$, $R^2 = 0.04$). Basic story content: frontal ($r(43) = -0.07$, $p = .6$, $R^2 = 0.005$), parietal ($r(43) = 0.24$, $p = .12$, $R^2 = 0.06$), temporal ($r = 0.07$, $p = .65$, $R^2 = 0.005$)]. This was also true when we collapsed all of these (non-word) question types (frontal, $r(43) = -0.11$, $p = .45$, $R^2 = 0.01$, parietal, $r(43) = 0.07$, $p = .63$, $R^2 = 0.005$, temporal, $r(43) = -0.07$, $p = .63$, $R^2 = 0.005$; Fig. 3B). Thus, it seems that the correlation between ISC and overall learning was largely driven by word learning rather than other types of learning. However, these non-significant findings may be partly due to the focus of our research question on novel word learning, such that the test phase included more questions about novel word learning than other individual types of questions (by a factor of four; see Discussion).

Finally, we performed a median-split analysis and found significant differences in overall ISC across ROIs between relatively strong versus weak learners (see Supplementary Information for more details).

4. Discussion

This study examined the relationship between neural synchrony and learning within a sample of preschool-aged children during naturalistic, joint book reading with an adult. The primary goal was to understand if patterns of intersubject neural synchrony would predict young children's learning of novel words. Broadly, children demonstrated the ability to learn information of varying levels of complexity from the book, including individual object labels, the functions of those objects within the story, and basic character information. We found that neural synchrony (measured with intersubject correlation) between children in parietal channels was significantly correlated with children's learning, both for learning of individual words as well as overall learning of story content, collapsed across question types. Each child's ISC provides a proxy for their neural alignment to a signature pattern of processing the story; we found that the closer each child's neural time series was to this signature pattern (especially in parietal cortex), the better they learned new words introduced throughout the story. This study provides the first evidence of a link between listener-listener (child-child) neural synchrony over the course of a story and real-time word learning. In particular, it suggests that joint book reading with an adult is a naturalistic context that nudges children closer to an ideal neural signature for learning new words.

Our findings build on previous work demonstrating that the brains of adult observers become synchronized in higher-order, default mode network areas (including parietal lobule and medial prefrontal cortex; Iacoboni et al., 2004) when they share a high-level understanding of a stimulus. When high-level understanding breaks down due to scrambling natural speech (Lerner et al., 2011) or translating it into a foreign language (Honey et al., 2012), lower-order sensory areas such as auditory cortex remain synchronized across participants, but synchrony in higher-order areas disappears, revealing that synchrony between participants is driven by more than simple exposure to the same input. Instead, it is based on joint engagement with semantic or narrative-level content. This previous adult work has consistently shown the involvement of both prefrontal and parietal regions in listeners' high-level interpretations of natural stories and movies (Iacoboni et al., 2004; Liu et al., 2017; Stephens et al., 2010; Yeshurun et al., 2017).

In contrast to these studies, which investigated the relationship between neural synchrony among adults and their processing of the "gist" or overall interpretation of a story, our study took the new approach of measuring synchrony between children and focusing on its relationship to novel word learning. We found that this relationship was significant only in parietal cortex. The lack of an effect in prefrontal cortex could be due to several factors. For instance, it is possible that in early childhood, parietal brain areas play a strong role in tracking narrative content, whereas the prefrontal cortex does not become functionally connected to the rest of the default mode network (as characterized in adults in the studies above) until later in development. Alternatively, the process of tracking individual words' meanings may be more strongly linked to attentional factors regulated by parietal cortex, in which case we would predict to see a similar pattern of results if we tested novel word learning in adults. Interestingly, when we divided our participants into two groups based on their overall learning across all question types (which is analogous to the comprehension tests in previous adult studies; see Supplementary Fig. 3), we did find a significant difference between high- and low-performing groups in parietal cortex as well as a trending difference in frontal cortex. Future research directly comparing the role of neural synchrony in learning multiple levels of information from stories—isolated novel object labels and their functions, character motives, and overall narrative arcs—in both adults and children will help clarify the mechanistic role of multiple brain areas in the moment-to-moment encoding, maintenance, and recall of natural input.

A likely explanation for the link between neural synchrony and learning is that children who attend to key structures in the story, and thus whose neural signals are more likely to reflect an "ideal" stimulus-driven signature (resulting in higher ISC), tend to learn more effectively. Children who attend to less relevant or useful aspects of the story, or who are disengaged entirely, will likely have neural signals that synchronize less successfully with those of the rest of the group and will tend to learn less effectively. Some have proposed that coupling may be a mechanism for entraining child learners' brains to the statistics of input by ensuring that learners' brains enter a phase of high excitability during optimal moments for encoding information (Wass et al., 2020). This phase entrainment could be accomplished via well-placed behavioral cues from adults during communicative interactions, or through the structure of a stimulus itself. Thus, listener-listener synchrony is emerging in developmental science as a powerful measure of shared attentional engagement with the dynamic structure of naturalistic stimuli. Its usefulness has been demonstrated repeatedly in adult research. One study found that during movie viewing, high emotional arousal was associated with neural synchronization in visual and dorsal attentional networks, suggesting that emotionally salient moments direct viewers' attention to similar features of the environment and facilitate shared understanding (Nummenmaa et al., 2012). Similarly, ISC is higher for rhetorically powerful political speeches (Schmälzle, Häcker, Honey, & Hasson, 2015), emotionally salient narratives (Kang & Wheatley, 2017), highly rated television content (Dmochowski et al., 2014), suspenseful movie segments (Schmälzle & Grall, 2020), and videos with strong health messages (Imhof, Schmälzle, Renner, &

Schupp, 2020). This widely reported relationship between audience engagement and neural synchrony calls for further research on the features of child-directed books and media (repetition, character emotions, vivid images) and social behaviors (gesture, prosody, gaze) that successfully entrain children's attentional networks and mediate learning. The manipulation of both of these factors could serve as a powerful test of the proposal that the more effectively an adult reader (or author) guides a child's brain toward an "ideal" neural signature, the better the child will learn (Wass et al., 2020). Beyond neuroimaging, pupil size synchrony, which has been found to predict young children's word learning (Nencheva, Piazza, & Lew-Williams, 2021), could be further harnessed to investigate how moment-to-moment attentional engagement with prosodic contours relates to neural representation of dynamic story content.

This work sheds new light on the neural underpinnings of early word learning but leaves open many possibilities for extending our findings. First, we currently know little about neural entrainment to the dynamics of natural communication across development. Previous electrophysiological and neuroimaging research with adults has analyzed dynamic changes in neural activation patterns in the hippocampus, left temporal lobe, and inferior frontal gyrus during word learning (Shtyrov, 2012), but young children's word learning is subject to a myriad of unique factors that distinguish this process from adult word learning. For example, when a preschooler hears a new word within a story, they are still learning how to integrate words within the context of long-timescale narrative arcs, and when an infant hears their parent say a new word, they are still learning to segment acoustic input into syllables. Thus, the aggregate of developmental processes impacting the learning of an individual word (including a child's current vocabulary) should be carefully considered in studies of language development, and approaches comparing child-child synchrony in multiple brain areas and across developmental stages will be particularly useful in this effort. Second, we focused primarily on novel word learning and included many test trials to capture it, but this made it difficult to fully assess the relationship between ISC and learning of other categories of information from the story. It could thus be possible, for example, that learning of object functions or character traits relates strongly to ISC, but we had relatively weaker power to examine those question types. To understand how neural synchrony relates to word learning *and* other types of information in storybooks, future studies with larger sample sizes might address this limitation by optimizing the sampling of different question types. Researchers might also explore how consistently children's brains process information that varies in complexity across timescales (e.g., individual words versus long-term character goals). This could be evaluated by investigating how structural disruptions of stories (e.g., via scrambling; Lerner et al., 2011) impact both neural synchrony in relevant brain areas as well as story comprehension.

Our study used a joint book reading paradigm, and this social form of engagement with language has been shown to benefit learning. While children have the ability to learn new words through passive listening to storytelling (Elley, 1989), studies of preschool-aged children suggest that interactive, shared reading facilitates greater vocabulary acquisition than passive listening (Hargrave & Sénéchal, 2000; Opel, Ameer, & Aboud, 2009; Whitehurst et al., 1988). Analyses of fully natural infant-adult shared reading experiences reveal that these interactions often take on a dialogic, contingent structure, with adult communication tailored to children's developmental level and real-time feedback (Dowdall et al., 2020; Ninio & Bruner, 1978; Vygotsky, 1978). To do so, caregivers adopt many behaviors that engage children and enhance word learning during book reading, such as recasting and repeating unfamiliar words, changing the content of their speech, asking 'what' and 'where' questions, and connecting story content to the child's personal experiences (Ard & Beverly, 2004; Hayden & Fagan, 1987; Ninio, 1980; Wheeler, 1983). Although the design of our story was naturalistic, our use of one experimenter and timed page-turns limited reader-child interaction to some degree. Interactions during everyday book reading are rich in back-and-forth communicative exchanges via speech, gesture, gaze, touch, and emotion (Suarez-Rivera et al., 2019). In the future, assessing how diverse parental behaviors, as well as children's level of social engagement, are reflected in children's neural representations during dialogic book reading may help us understand why this type of interaction positively affects language outcomes. Incorporating children's own caregivers into future fNIRS studies, and characterizing other family-specific factors such as socioeconomic status, education, and cultural background, will provide insights into the neural mechanisms supporting parents' tailoring of behavioral cues to promote joint attention.

Although technical limitations prevented us from analyzing the role of adult-child coupling in learning (see Supplementary Fig. 1), this is an exciting area for future research. Recent EEG (Pan et al., 2020) and fMRI (Nguyen et al., 2020; Meshulam et al., 2021) studies of adults have begun to explore the relationship between teacher-student coupling and learning outcomes, but the arena of early, interactive learning from caregivers is underexplored. Future research could investigate the role of different behavioral cues (prosody, eye gaze, gesture) at key moments in a story, such as before or after initial exposure to a novel word, in aligning children's neural representations of semantic content with the adult storyteller's representations. Additionally, although our analyses focused on mirrored, one-to-one synchrony between the child listeners' brains, adult-child interactions are more likely characterized by non-mirrored coupling functions (Hasson & Frith, 2016). For example, leader-follower relationships (which might occur when an adult has prior knowledge that enables faster anticipation of plot development compared to a child) could be evaluated using lagged neural synchrony measures. In a more improvisational context (such as during free play), the two brains may synergistically constrain or adapt to each other to invent new content together. To further understand the link between adult-child neural coupling and word learning, it will be fruitful to track how a wide range of coupling patterns maps onto different developmental stages and interaction contexts.

Acknowledgements

We thank the participating families and the members of the Princeton Baby Lab, especially Sagi Jaffe-Dax, Naiqi Xiao, and Annie Schwartzstein. This work was supported by a Princeton University C. V. Starr Fellowship to E.A.P., grants from the National Institute of Child Health and Human Development to C.L.W. (R01HD095912, R03HD079779) and from the National Institutes of Health to E.A.P. (5DP1HD091948), and a grant from the Yeager Family Foundation to C. L.W.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2021.104752.

OSF link where the data are stored: https://osf.io/cmx8d/

References

Ard, L. M., & Beverly, B. L. (2004). Preschool word learning during joint book reading: Effect of adult questions and comments. *Communication Disorders Quarterly, 26*(1), 17–28.

Bus, A. G., van IJzendoorn, M. H., & Pellegrini, A. D. (1995). Joint book reading makes for success in learning to read: A meta-analysis on intergenerational transmission of literacy. *Review of Educational Research, 65*(1), 1–21.

Cui, X., Bray, S., & Reiss, A. L. (2010). Functional near infrared spectroscopy (NIRS) signal improvement based on negative correlation between oxygenated and deoxygenated hemoglobin dynamics. *NeuroImage, 49*(4), 3039.

Dickinson, D. K., Griffith, J. A., Golinkoff, R. M., & Hirsh-Pasek, K. (2012). How reading books fosters language development around the world. *Child Development Research, 602807*.

Dmochowski, J. P., Bezdek, M. A., Abelson, B. P., Johnson, J. S., Schumacher, E. H., & Parra, L. C. (2014). Audience preferences are predicted by temporal reliability of neural processing. *Nature Communications, 5*(1), 1–9.

Dowdall, N., Melendez-Torres, G. J., Murray, L., Gardner, F., Hartford, L., & Cooper, P. J. (2020). Shared picture book reading interventions for child language development: A systematic review and meta-analysis. *Child Development, 91*, e383–e399.
Elley, W. B. (1989). Vocabulary acquisition from listening to stories. *Reading Research Quarterly, 24*(2), 174–187.
Ferguson, B., & Lew-Williams, C. (2016). Communicative signals support abstract rule learning by 7-month-old infants. *Scientific Reports, 6*, 25434.
Goldstein, M. H., King, A. P., & West, M. J. (2003). Social interaction shapes babbling: Testing parallels between birdsong and speech. *Proceedings of the National Academy of Sciences, 100*(13), 8030–8035.
Goldstein, M. H., & Schwade, J. A. (2008). Social feedback to infants' babbling facilitates rapid phonological learning. *Psychological Science, 19*(5), 515–523.
Hargrave, A. C., & Sénéchal, M. (2000). A book reading intervention with preschool children who have limited vocabularies: The benefits of regular reading and dialogic reading. *Early Childhood Research Quarterly, 15*(1), 75–90.
Hasson, U., & Frith, C. D. (2016). Mirroring and beyond: Coupled dynamics as a generalized framework for modelling social interactions. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 371*(1693), Article 20150366.
Hasson, U., Nir, Y., Levy, I., Fuhrmann, G., & Malach, R. (2004). Intersubject synchronization of cortical activity during natural vision. *Science, 303*(5664), 1634–1640.
Hayden, H. M. R., & Fagan, W. T. (1987). Keeping it in context: Strategies for enhancing literacy awareness. *First Language, 7*(20), 159–171.
Honey, C. J., Thompson, C. R., Lerner, Y., & Hasson, U. (2012). Not lost in translation: Neural responses shared across languages. *Journal of Neuroscience, 32*, 15277–15283.
Horst, J. S., & Hout, M. C. (2016). The novel object and unusual name (NOUN) database: A collection of novel images for use in experimental research. *Behavior Research Methods, 48*(4), 1393–1409.
Iacoboni, M., Lieberman, M. D., Knowlton, B. J., Molnar-Szakacs, I., Moritz, M., Throop, C. J., & Fiske, A. P. (2004). Watching social interactions produces dorsomedial prefrontal and medial parietal BOLD fMRI signal increases compared to a resting baseline. *NeuroImage, 21*(3), 1167–1173.
Imhof, M. A., Schmälzle, R., Renner, B., & Schupp, H. T. (2020). Strong health messages increase audience brain coupling. *NeuroImage, 116527*.
Kang, O., & Wheatley, T. (2017). Pupil dilation patterns spontaneously synchronize across individuals during shared attention. *Journal of Experimental Psychology: General, 146*(4), 569–576.
Kopp, C. B. (1982). Antecedents of self-regulation: A developmental perspective. *Developmental Psychology, 18*, 199–214.
Kuhl, P. K., Tsao, F.-M., & Liu, H.-M. (2003). Foreign-language experience in infancy: Effects of short-term exposure and social interaction on phonetic learning. *Proceedings of the National Academy of Sciences, 100*(15), 9096–9101.
Lerner, Y., Honey, C. J., Silbert, L. J., & Hasson, U. (2011). Topographic mapping of a hierarchy of temporal receptive windows using a narrated story. *Journal of Neuroscience, 31*, 2906–2915.
Liu, Y., Piazza, E. A., Simony, E., Shewokis, P. A., Onaral, B., Hasson, U., & Ayaz, H. (2017). Measuring speaker–listener neural coupling with functional near infrared spectroscopy. *Scientific Reports, 7*, 43293.
Malonek, D., & Grinvald, A. (1996). Interactions between electrical activity and cortical microcirculation revealed by imaging spectroscopy: Implications for functional brain mapping. *Science, 272*, 551–554.
Meshulam, M., Hasenfratz, L., Hillman, H., Liu, Y. F., Nguyen, M., Norman, K. A., & Hasson, U. (2021). Neural alignment predicts learning outcomes in students taking an introduction to computer science course. *Nature communications, 12*(1), 1–14.
Miller, J. L., Ables, E. M., King, A. P., & West, M. J. (2009). Different patterns of contingent stimulation differentially affect attention span in prelinguistic infants. *Infant Behavior and Development, 32*, 254–261.
Mundy, P., Block, J., Delgado, C., Pomares, Y., Hecke, A. V. V., & Parlade, M. V. (2007). Individual differences and the development of joint attention in infancy. *Child Development, 78*(3), 938–954.
Nencheva, M., Piazza, E. A., & Lew-Williams, C. (2021). The moment-to-moment pitch dynamics of child-directed speech shape toddlers' attention and learning. *Developmental Science, 24*(1), Article e12997.
Nguyen, M., Chang, A., Micciche, E., Meshulam, M., Nastase, S. A., & Hasson, U. (2020). Teacher-student neural coupling during teaching and learning. *bioRxiv*. https://doi.org/10.1101/2020.05.07.082958.
Nguyen, T., Schleihauf, H., Kayhan, E., Matthes, D., Vrtička, P., & Hoehl, S. (2020). The effects of interaction quality on neural synchrony during mother-child problem solving. *Cortex, 124*, 235–249.
Ninio, A. (1980). Picture-book reading in mother-infant dyads belonging to two subgroups in Israel. *Child Development, 51*(2), 587–590.
Ninio, A., & Bruner, J. (1978). The achievement and antecedents of labelling. *Journal of Child Language, 5*(1), 1–15.
Noble, C., Sala, G., Peter, M., Lingwood, J., Rowland, C., Gobet, F., & Pine, J. (2019). The impact of shared book reading on children's language skills: A meta-analysis. *Educational Research Review, 28*, 100290.
Nummenmaa, L., Glerean, E., Viinikainen, M., Jääskeläinen, I. P., Hari, R., & Sams, M. (2012). Emotions promote social interaction by synchronizing brain activity across individuals. *Proceedings of the National Academy of Sciences, 109*(24), 9599–9604.
Opel, A., Ameer, S. S., & Aboud, F. E. (2009). The effect of preschool dialogic reading on vocabulary among rural Bangladeshi children. *International Journal of Educational Research, 48*, 12–20.
Pan, Y., Dikker, S., Goldstein, P., Zhu, Y., Yang, C., & Hu, Y. (2020). Instructor-learner brain coupling discriminates between instructional approaches and predicts learning. *Neuroimage, 211*, 116657.
Parish-Morris, J., Mahajan, N., Hirsh-Pasek, K., Golinkoff, R. M., & Collins, M. F. (2013). Once upon a time: Parent-child dialogue and storybook reading in the electronic era. *Mind, Brain, & Education, 7*, 200–211.
Piazza, E. A., Hasenfratz, L., Hasson, U., & Lew-Williams, C. (2020). Infants and adults are coupled to the dynamics of natural communication. *Psychological Science, 31*, 6–17.
Reich, S. M., Yau, J. C., & Warschauer, M. (2016). Tablet-based eBooks for young children: What does the research say? *Journal of Developmental & Behavioral Pediatrics, 37*, 585–591.
Schmälzle, R., & Grall, C. (2020). The coupled brains of captivated audiences: An investigation of the collective brain dynamics of an audience watching a suspenseful film. *Journal of Media Psychology: Theories, Methods, and Applications, 32*(4), 187–199.
Schmälzle, R., Häcker, F. E., Honey, C. J., & Hasson, U. (2015). Engaged listeners: Shared neural processing of powerful political speeches. *Social Cognitive and Affective Neuroscience, 10*(8), 1137–1143.
Scholkmann, F., Spichtig, S., Muehlemann, T., & Wolf, M. (2010). How to detect and reduce movement artifacts in near-infrared imaging using moving standard deviation and spline interpolation. *Physiological measurement, 31*(5), 649.
Sheth, S. A., Nemoto, M., Guiou, M., Walker, M., Pouratian, N., & Toga, A. W. (2004). Linear and nonlinear relationships between neuronal activity, oxygen metabolism, and hemodynamic responses. *Neuron, 42*, 347–355.
Shtyrov, Y. (2012). Neural bases of rapid word learning. *The Neuroscientist, 18*, 312–319.
Silbert, L. J., Honey, C. J., Simony, E., Poeppel, D., & Hasson, U. (2014). Coupled neural systems underlie the production and comprehension of naturalistic narrative speech. *Proceedings of the National Academy of Sciences of the United States of America, 111*(43), E4687–E4696.
Stephens, G. J., Silbert, L. J., & Hasson, U. (2010). Speaker-listener neural coupling underlies successful communication. *Proceedings of the National Academy of Sciences of the United States of America, 107*(32), 14425–14430.
Striano, T., Chen, X., Cleveland, A., & Bradshaw, S. (2006). Joint attention social cues influence infant learning. *European Journal of Developmental Psychology, 3*(3), 289–299.
Suarez-Rivera, C., Smith, L. B., & Yu, C. (2019). Multimodal parent behaviors within joint attention support sustained attention in infants. *Developmental Psychology, 55*, 96–109.
Tomasello, M. (1992). The social bases of language acquisition. *Social Development, 1*(1), 67–87.
Vygotsky, L. (1978). Interaction between learning and development. In M. Gauvain, & M. Cole (Eds.)*, Vol. 23. Readings on the development of children* (pp. 34–41). New York, NY: Scientific American Books.
Wass, S. V., Whitehorn, M., Haresign, I. M., Phillips, E., & Leong, V. (2020). Interpersonal neural entrainment during early social interaction. *Trends in Cognitive Sciences, 24*(4), 329–342.
Wheeler, M. P. (1983). Context-related age changes in mothers' speech: Joint book reading. *Journal of Child Language, 10*(1), 259–263.
Whitehurst, G. J., Falco, F. L., Lonigan, C. J., Fischel, J. E., DeBaryshe, B. D., Valdez-Menchaca, M. C., & Caulfield, M. (1988). Accelerating language development through picture book reading. *Developmental Psychology, 24*(4), 552–559.
Wilson, S. M., Molnar-Szakacs, I., & Iacoboni, M. (2008). Beyond superior temporal cortex: Intersubject correlations in narrative speech comprehension. *Cerebral Cortex, 18*(1), 230–242.
Yeshurun, Y., Nguyen, M., & Hasson, U. (2021). The default mode network: where the idiosyncratic self meets the shared social world. *Nature Reviews Neuroscience*, 1–12.
Yeshurun, Y., Swanson, S., Simony, E., Chen, J., Lazaridi, C., Honey, C. J., & Hasson, U. (2017). Same story, different story: The neural representation of interpretive frameworks. *Psychological Science, 28*(3), 307–319.