Listening to a Story or Creating One: Children's Performances and Brain Activity in Storytelling-Based Learning

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Abstract

Children learn better through shared social experiences. Particularly, storytelling is a successful learning strategy that facilitates learning. These shared experiences are reflected in neural synchrony, which underlies predict understanding of the learned information. For adults, the scaffolding strategy, a shared social experience that involves active engagement rather than passive listening, has been shown to promote learning and has been linked with higher neural synchrony compared to passive learning. However, in the context of storytelling, it is unclear whether children will perform higher levels of neural synchrony as well as improved performances when they scaffold the learned information (tell a story about it) compared to when they passively listen. Here, we compare learning outcomes and neural basis of two learning strategies in young school-aged children in the context of storytelling.

Keywords: Social interactive learning; Brain-to-brain coupling; Storytelling; fNIRS hyperscanning

Introduction

For young children, learning novel words and their functions is highly dependent on social engagement with adults and other children (Tomasello, 1992). This engagement often takes the form of storytelling. Storytelling and story reading have been found to be successful educational strategies that improve language acquisition (Miller & Pennycuff, 2008; Speaker et al., 2004), reading comprehension (Craig et al., 2001, Rahiem, 2021), and understanding of basic mathematics and science (Casey, Erkut, & Young, 2008; Hu et al., 2020; Pramling & Samuelsson, 2008). The engaging nature of storytelling can be achieved in two ways: either telling the child a story (passive storytelling) or encouraging the child to tell the story themselves (active storytelling). The latter option might be seen as an expression of an active learning strategy called scaffolding. Scaffolding is characterized by constructive engagement behaviors that redirect learners' actions and understanding, such as asking key questions and providing feedback and hints (Chi & Wylie, 2014). This strategy requires more bidirectional exchange between instructors and learners and has been shown to promote learning successfully (Pan et al., 2020). While the advantages of storytelling and scaffolding as learning strategies have been vastly studied, research on their neural substrate and underlying mechanisms is still in its early stages.

Several neuroimaging works have begun to characterize the neural activity that is associated with learning in a natural continuous setting. Some did it by measuring simultaneously the brain activities of the instructor and the learner while interacting and examining the teacher-learner neural synchrony (i.e., coupling; Hasson et al., 2012). These studies suggest that the extent of interaction between the instructor and the learner can be reflected in the degree of coupling between their brain activities (Nguyen et al., 2022; Stephens, Silbert & Hasson, 2010). Other studies focused on detecting the listener-listener neural synchrony (inter-subject correlation, ISC), to quantify how similarly the dynamics of external input are represented across different listeners' brains (Piazza et al., 2021; Zadbood et al., 2017). In both methods, the synchrony was found to occur in regions linked to the Default Mode Network (DMN), and was correlated with listener comprehension (Nguyen, Vanderwal & Hasson., 2019; Yeshurun, Nguyen & Hasson., 2021).

Recent studies have employed these methods to explore the neural mechanisms of storytelling and scaffolding. In their fNIRS study, Piazza et al. (2021) demonstrated that preschoolers can acquire a range of semantic information from a story reading session and showed that child-child neural synchrony in the parietal cortex predicts word learning. On the other hand, Pan et al. (2020) found that scaffolding-based learning resulted in better learning outcomes and was associated with increased instructor-learner brain coupling in prefrontal regions when compared to explanation-based learning. Nevertheless, these two studies did not integrate the storytelling and the scaffolding strategies and only focused on one neural synchrony measurement, leaving a fragmented understanding.

Our study aimed to bridge this gap by investigating the potential benefits and underlying neuronal mechanisms of scaffolding within the context of storytelling. We track the neural processes that enable the transfer of information across brains during storytelling, and explore if it differs when a child listens passively to the story (passive storytelling) versus being encouraged to tell it themselves (scaffolding storytelling).

First-grade-age children participated in an interactive learning session with an instructor, that employed either passive storytelling or scaffolding storytelling. Using fNIRS, we recorded neural activity in the prefrontal cortex, premotor cortex, temporal lobes, and parietal lobes, from both children and the instructor. We conducted a child-child ISC analysis and a child-instructor synchronization analysis. In accordance with Pan et al. (2020), we hypothesized that scaffolding would lead to better learning and would be associated with higher child-instructor neural synchrony. Moreover, we hypothesize that child-instructor synchrony would have a distinct pattern for each learning strategy. Additionally, we expected that the learning would be driven by the interactive sessions, therefore we assumed that the

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level of ISC of the children's brain activity during the videos would be positively correlated but would not predict learning.

Methods

Participants

Thirty-three children were recruited for the study. All children arrived with their parents, who signed an informed consent and assent was obtained from the children prior to their participation. The study and procedure were approved by the Tel Aviv University IRB. Parents were allowed to sit behind their child in the experiment room without being within their view. Nine subjects were excluded from the final data analysis: five due to technical problems, three due to being in the second grade rather than the first grade, and one due to suspicion of cognitive disability. The remaining 24 participants (age 6.9±0.3 years, 14 females) were included in the analysis. The instructor was an undergraduate psychology student who remained blind to the experiment's purpose and hypotheses.

Procedure

Children learned two sets of learning materials – one in each strategy. Each set included four objects that were presented as tools for fixing a rocket ship or an air balloon. In each condition, the children first watched a short video presenting the objects fixing the vehicle, then participated in an interactive session with the instructor. During the interactive session, the instructor employed either Passive strategy (telling the child a scripted story about the learning subject) or Scaffolding strategy (encouraging the child to create their own story about it). To enhance the storytelling experience, the instructor presented the child with a cardboard featuring a picture of the vehicle from the video, along with four cards displaying the current stimuli, and a finger puppet of a dragon or an owl that was presented as the owner of the vehicle. For each subject, the instructor's strategy, the set of learning materials, and the puppet finger were randomly selected. The order of the conditions was counterbalanced between children. The two learning sessions did not differ in length [1st session: 149.0 ± 13.9 vs 2nd session: 153.2 ± 16.8 sec, $t(23) = -1.1$, $p = 0.3$; Passive: 151.8 ± 19.9 vs. Scaffolding: 150.4 ± 9.6 sec, $t(23) = 0.4$, $p = 0.7$]. After each interactive session, the children participated in a three-alternative forced-choice learning assessment to measure their novel word learning. The test had eight questions, four about the objects' names and the others about the objects' functions. During the experiment, children's and instructor's brain activity was recorded simultaneously via fNIRS-based hyperscanning. The videos were presented on a 43" screen positioned about 1.6 m from the child. The sessions were recorded with a Logitech Brio 4k camera that was positioned above the screen. The recordings were later annotated to indicate mutual gaze and the number of times the instructor mentioned the objects' names and functions.

Materials and stimuli

The stimuli objects, to which children were unlikely to have had previous exposure, were selected from the Novel Object and Unusual Name (NOUN) database (Horst & Hout, 2016). The stimuli in each set had similar familiarity scores (21.2% ± 13.4 vs. 21.5% ± 13.3) and were comparable to each other within the same set, as well as to the stimuli in the other set (the similarity was based on Euclidean distance, 0.41 ± 0.05 vs. 0.41 ± 0.04; 0.48 ± 1.5). Some objects had their colors altered using Adobe Photoshop software to reduce color similarity. The randomly assigned names for the objects were Hebrew pseudowords (e.g., "Badif" and "Azfa"; Deutsch & Bentin, 1996).

fNIRS acquisition

A NIRSport2 device (NIRx) was used to record the neural activity of the dyads. A cap with 44 channels (16 sources and 15 detectors) was placed on the child and the instructor. The channels covered the prefrontal cortex, the premotor cortex, the temporal lobes, and the parietal lobes, all in both hemisphere (Fig. 4). These eight regions of interest (ROI) cover cortical regions that were previously associated with the Default Mode Network (DMN) such as ventromedial and dorsomedial prefrontal cortex, bilateral temporoparietal junction, and inferior parietal lobule (Yeshurun et al., 2021). The premotor cortex was chosen because it is associated with attention networks, language comprehension, and visual learning (e.g. frontal eye field; Corbetta & Shulman, 2002; Wilson, Molnar-Szakacs, & Iacoboni, 2008). Eight short channels, four for each hemisphere, were used to remove superficial physiological noise. Near-infrared absorption rates (at two wavelengths: 760 and 850 nm) were measured with a sampling rate of 5.08 Hz. Oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentrations were extracted using the modified Beer-Lambert law. The focus of the analysis was on HbO concentration, for which the signal-to-noise ratio is better than HbR (Mahmoudzadeh et al., 2013), and has been used as an indicator to compute brain-to-brain coupling (Pan et al., 2020).

fNIRS preprocessing

Signals were pre-processed using Satori software (NIRx). A signal quality control was applied on each SNIRF file, wherein channels with a coefficient of variation above 30% were excluded from the analysis. The raw wavelength data was converted to optical density, and a Butterworth band pass filter of 0.5 to 0.01 Hz was applied. Then, a short-channel regression (closest SSR) and a spike removal were performed (Iteration:10; Lag: 5 seconds; Threshold: 3.50; Influencer: 0.50). Finally, the optical density data was converted to concentration data and normalized with z-transformation.

STORM-Net digitizing tool was used to accurately estimate the channels' position of the fNIRS cap mounted on a subject's head, based on a short video of the subject wearing the cap (Erel et al., 2021) The application outputs the coordinates of every point of interest on the cap in (a statistical) MNI coordinate system. For each subject, the channels were separated into the different chosen ROIs based on their estimated coordinates. The data was averaged across channels within each ROI. All subsequent analyses were performed based on the averaged signal of each ROI.

fNIRS analysis

Child-child Inter-subject correlation (ISC) analysis: The ISC analysis was based on the children's brain activity while watching the videos. A Pearson correlation was calculated between the brain activity of each subject and the averaged brain activity of the whole group of children without that subject. The calculation was done for each ROI separately, resulting eight Pearson correlation values for each subject. The Pearson R values were transformed using Fisher's R to Z transformation (ISC scores). To examine the relationship between ISC scores and performance, a Pearson correlation and a linear least-squares regression were conducted for performance and ISC scores in each ROI.

Child-instructor neural synchrony analysis: The instructor's signals from the interactive sessions were preprocessed as described above. For each interactive session of each dyad, a Pearson correlation was calculated between each child's ROI and each instructor's ROI, resulting a correlation matrix of 64 paired regions. To compare the overall child-instructor neural synchrony level between conditions, cumulative distribution functions (CDF) of Pearson's R values were calculated for both Scaffolding and Passive sessions, as well as Kolmogorov-Smirnoff test for equal distributions.

Next, a pattern analysis of the child-instructor neural synchrony was made. First, a paired t-test was employed to compare the ROIs' R values between the two strategies. Second, to identify paired ROIs that are significantly correlated, the R values of each learning strategy transformed using Fisher's R to Z transformation and the subjects' Z values in each ROI were compared to 0 with a one-sample T-test. The calculation yielded two p-values maps, one for each strategy. Third, a classification test was performed to determine whether the different learning conditions had distinct patterns of child-instructor synchrony. The distance between the correlation matrix of each dyad and the averaged correlation matrix of the group without them was calculated. The group-averaged matrix originated from either the same condition or from the other one.

Previous studies showed that the neural responses of listeners can lag or precede those of the speaker, facilitating comprehension and anticipation, respectively (Liu et al., 2017). To capture the temporal structure of the child–instructor interaction, the child's time course was shifted with respect to those of the instructor from −20 sec to 20 sec in 1 sec increments. A positive shift signifies the child leading, while a negative shift indicates the instructor leading.

Results

Storytelling is an effective learning strategy that benefits from the scaffolding approach

For both conditions, the overall learning was significantly above chance [Scaffolding: 6.1 ± 1.6, t(23) = 6.4, $p < 0.001$; Passive: 5.7 ± 1.4, t(23) = 6.0, $p < 0.001$, one sample t-test]. Learners' performances were better for objects' functions compared to objects' names in both conditions [Scaffolding: 3.5 ± 0.8 vs. 2.6 ± 1.2, t(23) = 3.4, $p < 0.005$; Passive: 3.8 ± 0.6 vs. 1.9 ± 1.2, t(23) = 6.2, $p < 0.001$]. Contrary to our hypothesis, the learning strategy did not affect learners' total scores [6.1 ± 1.6 vs. 5.7 ± 1.4, t(23) = 0.9, $p = 0.2$], probably due to a ceiling effect in learning the functions (max score was 4 in each condition). Nevertheless, we did find a significant advantage for Scaffolding in word learning (objects' names) compared to Passive [2.6 ± 1.2 vs. 1.9 ± 1.2, t(23) = 1.8, $p < 0.05$; Fig. 1]. The effect of the learning strategy was greater for words than for functions [F(1, 23) = 5.8, $p < 0.05$, repeated measures ANOVA].

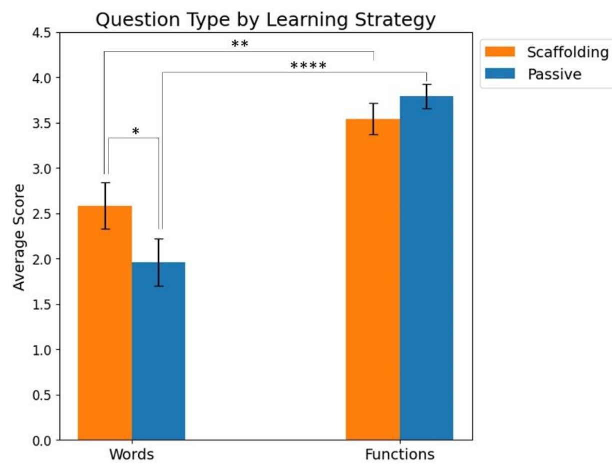

Figure 1: Performance by learning strategy and question type. There were 8 questions in each test, 4 about the objects' names (Words) and the other about the objects' functions (Functions). In each strategy, there were better results for the objects' function rather than their names. [Scaffolding: t(23) = 3.4, $p < 0.005$; Passive: t(23) = 6.2, $p < 0.001$]. The subjects had better results for questions about the names in the Scaffolding condition than in the Passive condition [t(23) = 1.8, $p < 0.05$]. N = 24.

Children learned functions better than names even though the instructor repeated the objects' names more times than their functions during both interactive sessions (Scaffolding: 11.5 ± 3.4 vs. 6.3 ± 2.2 times, t(22) = 12.2, $p < 0.001$; Passive: 19.1 ± 2.4 vs. 11.6 ±1.1 times, t(22) = 26.6, $p < 0.001$). Importantly, words were better learned in the Scaffolding condition even though the instructor repeated the objects' names more times in the Passive condition (11.5 ± 3.4 vs. 19.1 ±2.4 times, t(22) = -6.5, $p < 0.001$). However, the children repeated the objects' names more times than their functions, in both conditions (Scaffolding: 3.6 ± 2.1 vs. 0.6 ±

1.1 times, t(22) = 5.9, $p < 0.001$; Passive: 0.3 ± 1.0 vs. 0.0 ±0.0 times). Interestingly, the overall number of times the instructor mentioned the objects' names and functions did not predict the subjects' overall scores [Scaffolding: r(22) = -0.07, p = 0.7 Passive: r(22) = -0.002, p = 0.992]. Nor did the length of the learning session [Scaffolding: r(23) = -0.17, p = 0.4; Passive: r(23) = 0.34, p = 0.1].

Child-child neural synchrony during video watching is positive and unrelated to learning

In each ROI, the brain activity of the vast majority of the children was positively correlated with the group-averaged brain activity (Fig. 2). This finding supports other research that reported inter-subject correlation (ISC) in the default mode network between subjects that watched the same stimuli (Simony et al., 2016; Yeshurun, et al., 2021). As expected, our results did not indicate a significant correlation between children's performances and their ISC values in any ROI. This finding strengthens the assumption that the learning was not driven by the video stage.

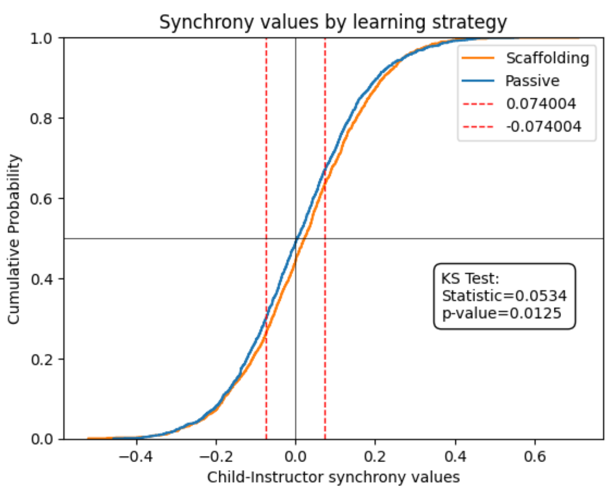

Figure 3: Child-instructor synchrony values by learning strategy. Cumulative distribution functions (CDF) of the Pearson's R values in Scaffolding (orange) and Passive (blue) sessions. The Pearson correlation between the child's brain activity and the instructor's brain activity was calculated for each ROI pair for each dyad (1536 pairs of ROIs). The dashed red lines represent the threshold Pearson values for a significant correlation ($p < 0.05$) with degrees of freedom ranging from 700 to 800—the average range for the degrees of freedom in the Child-instructor data. The black lines denote the center of a null distribution (cumulative probability of 0.5 and synchrony of 0). Across all pairs of ROIs and all dyads, the neural synchrony during Scaffolding sessions was stronger than during the Passive sessions. The distribution of synchrony values was different between the two learning strategies (KS = 0.05, p = 0.01, Kolmogorov-Smirnoff test for equal distributions).

Child-instructor neural synchrony is overall higher in Scaffolding storytelling than in Passive story-listening

Overall, across all ROI pairs, Child-Instructor synchronization during the scaffolding sessions was higher than during the passive sessions, as indicated by the cumulative distribution synchronization values in both conditions (Fig. 3).

Child-instructor synchrony had a distinct pattern for each learning strategy

The Child-Instructor neural synchrony has different patterns when the child is encouraged to create the story (Scaffolding) compared to when he passively listens to it (Passive). During the Scaffolding sessions, the neural activity of the children and the instructor was in synchrony in five pairs of ROIs (Table 1 and Fig. 4a). Interestingly, the synchrony was mainly between the children's left prefrontal cortex and the instructor's right hemisphere ROIs. In most ROI pairs, the peak of the lag plot of the correlation values was slightly before the neutral time (lag = 0), in which there was no shifting in time. Namely, the neural activity of the instructor during the interaction was leading the child's neural activity. However, when the child's left prefrontal cortex was coupled to the instructor's right parietal, the peak of correlation lagged slightly after the neutral time, indicating that the neural activity of the child led the instructor's neural activity.

For Passive sessions, however, the patterns of neural synchrony between instructor and child were different (Fig. 4b). During the Passive sessions, the neural activity of the children and the instructor was in synchrony in three pairs of ROIs, all of them in the right hemispheres of the child and the instructor (Table 1). Only in the synchrony of the child's right premotor cortex and the instructor's right premotor cortex, the instructor's activity was ahead of the child's during the interaction. Moreover, in contrast to the Scaffolding sessions, not all synchronies were positive during the Passive session: there was negative synchrony between the child's activity in the right temporal lobe and the instructor's activity in the right parietal lobe.

Table 1: Significant child-instructor neural synchrony by ROI. R – right, L – left. * $p < 0.05$, ** $p < 0.005$

	Child ROI	**Instructor ROI**	**t(23)**
Scaffolding	Prefrontal-L	Prefrontal-R	3.4**
	Prefrontal-L	Premotor-R	3.3**
	Prefrontal-L	Temporal-R	2.2*
	Prefrontal-L	Parietal-R	2.7*
	Temporal-R	Premotor-R	2.1*
Passive	Premotor-R	Premotor-R	2.3*
	Premotor-R	Prefrontal-R	3.4**
	Temporal-R	Parietal-R	-3.3**

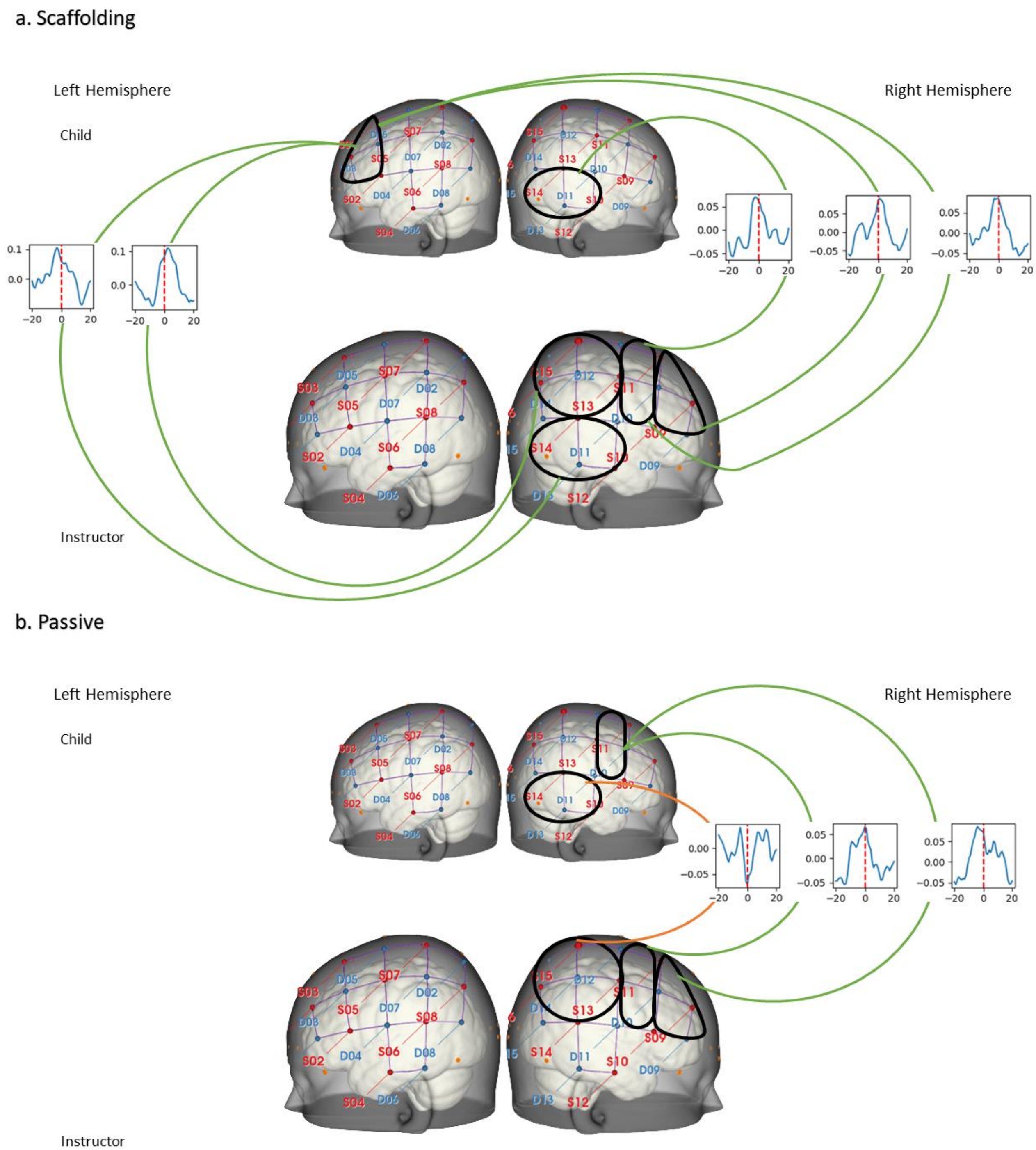

Figure 4: Child-instructor neuronal synchrony pattern by learning strategy. Scaffolding session (a) and the Passive session (b). The ROIs that were found to be significantly correlated ($p < 0.05$, permutation testing n=1000) are circled in black and connected with a curve. A green curve represents a positive correlation, while an orange curve represents a negative correlation. The averaged child-instructor correlation of all dyads is presented in a lag plot. The x-axis represents the time shift in seconds between the child and the instructor, with positive values indicating the child is ahead of the instructor and negative values indicating the instructor is ahead of the child. The neutral time (lag = 0) is marked with a red line. In Scaffolding sessions, in most ROIs the instructor is ahead of the child (the peak is slightly before lag = 0). In Passive sessions, however, the instructor is ahead of the child only in one ROI. N = 24.

These patterns of synchrony were overall different between the two learning strategies. For the majority of the dyads, the Euclidean distance between their correlation map and the group-averaged map was shorter when the group-averaged map was from the same condition and was classified correctly ($d' = 1.28$; $p < 0.05$).

Discussion

We examined the neural mechanism and learning performances associated with child-instructor storytelling learning sessions, and showed that children can learn in both passive and scaffolding storytelling sessions (listening to a story or being encouraged to create one). In both strategies, the interactive learning session was found to be associated with child-instructor brain coupling in regions linked to the Default Mode Network (DMN) and to attention networks. Nevertheless, scaffolding strategy was more effective than passive strategy in learning novel words and elicited higher and vaster neural coupling, mostly between the child's left prefrontal cortex and the instructor's right hemisphere. Moreover, during scaffolding learning the instructor's neural activity led the interaction in most coupled regions, while during passive listening there was no clear leader of the neural synchrony. These patterns are distinct, implying the neural mechanism associated with storytelling differs when the child is encouraged to tell the story or just listen to it.

This study presents a novel finding about the advantage of scaffolding in the context of storytelling. Until now, research has not examined the potential benefit of encouraging children to tell a story about a learning subject to improve their recall of new words. Rather, research has focused on analyzing the children's overall language abilities and their story-retelling skills that reflected from their stories (Cain & Oakhill, 1996; Kulkofsky & Klemfuss, 2008; Panc, Georgescu & Zaharia, 2015; Pappas & Pettegrew, 1991). Our paper offers a new view in the storytelling research field, that potentially can be applied in pedagogical environments.

The superiority of scaffolding in the context of storytelling is supported by the Interactive-Constructive-Active-Passive theory (ICAP, Chi & Wylie, 2014). According to ICAP, constructive engagements that are expressed in scaffolding (e.g., children generate their own understanding from instructors' guidance by creating a story) are more effective than passive engagements (e.g., children passively listen to the instructor's story). According to ICAP, the scaffolding strategy requires more bidirectional exchange between the instructor and learners compared to the passive strategy, which previous research in adults has suggested to be reflected in the learner-instructor degree of coupling (Pan et al., 2020).

It is possible to explain the neural mechanism underlying the difference between scaffolding-storytelling and passive-storytelling as follows: scaffolding strategy leads to better results because it involves more constructive engagement that deepens the comprehension. This constructive engagement requires more bidirectional exchange compared to passive engagement, and in turn is reflected in higher coupling levels in regions linked to the Default Mode Network (DMN) and to attention networks. In line with previous studies, we found that the better results of scaffolding are associated with its higher level of neural synchrony during interactive learning session. Specifically, this synchrony involves mostly the learner's neural activity in the left prefrontal cortex. In addition to its role in the DMN, the prefrontal cortex has a key role in cognitive control, attention, and goal-directed behaviors. (Miller & Cohen, 2001). Thus, the bidirectional exchange of information during scaffolding learning engages prefrontal areas to a greater extent.

The prefrontal cortex's dominance during scaffolding session aligns with prior research which found similar coupling exclusively during scaffolding (Pan et al., 2020), and with other fNIRS social interaction studies (Holper et al., 2013; Piazza et al., 2020). Additionally, the child's left prefrontal cortex leading the instructor's parietal region is consistent with findings by Liu et al. (2017), who observed a similar pattern in speaker-listener interactions.

Our behavioral results are limited to the learning of novel words, due to a ceiling effect in learning the functions of the new objects. Our neuroimaging results were constrained by the limitations of fNIRS, where only superficial cortical regions are accessible, and no other regions of the DMN (e.g., medial regions). Finally, while using the same instructor had an advantage as it is closer to a natural experience with one teacher, it is possible that the instructor's level of concentration varied between sessions. Additionally, it is possible that the instructor understood the study's hypothesis and biased her behavior accordingly. However, there were no significant differences in the children's results between the first and last sessions and the instructor did not report specific understanding of the hypothesis by the end of the study.

Using different neuroimaging methods such as fMRI, future studies could further investigate the pattern of child-instructor coupling during storytelling, while addressing more DMN regions. Moreover, giving the involvement of the premotor cortex in the coupling mechanism associated with storytelling, it would be interesting to explore more its role in shared experiences and interactive learning. Another possible direction is investigating the correlation between mutual eye gaze during storytelling to children's performances and child-instructor brain coupling. It would be intriguing to see if the differences between scaffolding and passive strategies in the context of storytelling reflects also in gaze synchrony.

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