



EEG phase synchronization during semantic unification relates to individual differences in children's vocabulary skill

Erin J. Panda^{1,2} | Zahra Emami^{1,3} | Taufik A. Valiante^{2,4,5} | Elizabeth W. Pang^{1,2,3}

¹Neurosciences and Mental Health, SickKids Research Institute, Peter Gilgan Centre for Research and Learning, The Hospital for Sick Children, Toronto, ON, Canada

²Epilepsy Research Program of the Ontario Brain Institute, Toronto, ON, Canada

³Division of Neurology, The Hospital for Sick Children, Toronto, ON, Canada

⁴Krembil Research Institute, University Health Network and Toronto Western Hospital, Toronto, Ontario, Canada

⁵Division of Neurosurgery, Department of Surgery, University of Toronto, Toronto, Ontario, Canada

Correspondence

Erin J. Panda (formerly Erin J. White), Neurosciences and Mental Health, SickKids Research Institute, Peter Gilgan Centre for Research and Learning, The Hospital for Sick Children, Toronto, Ontario, Canada.
Email: epanda@brocku.ca

Present address

Erin J. Panda, Department of Child and Youth Studies, Brock University, St. Catharines Ontario, Canada

Funding information

Ontario Brain Institute, Grant/Award Number: Epilepsy Research Program

Abstract

As we listen to speech, our ability to understand what was said requires us to retrieve and bind together individual word meanings into a coherent discourse representation. This so-called semantic unification is a fundamental cognitive skill, and its development relies on the integration of neural activity throughout widely distributed functional brain networks. In this proof-of-concept study, we examine, for the first time, how these functional brain networks develop in children. Twenty-six children (ages 4–17) listened to well-formed sentences and sentences containing a semantic violation, while EEG was recorded. Children with stronger vocabulary showed N400 effects that were more concentrated to centroparietal electrodes and greater EEG phase synchrony (phase lag index; PLI) between right centroparietal and bilateral frontocentral electrodes in the delta frequency band (1–3 Hz) 1.27–1.53 s after listening to well-formed sentences compared to sentences containing a semantic violation. These effects related specifically to individual differences in receptive vocabulary, perhaps pointing to greater recruitment of functional brain networks important for top-down semantic unification with development. Less skilled children showed greater delta phase synchrony for violation sentences 3.41–3.64 s after critical word onset. This later effect was partly driven by individual differences in non-verbal reasoning, perhaps pointing to non-verbal compensatory processing to extract meaning from speech in children with less developed vocabulary. We suggest that functional brain network communication, as measured by momentary changes in the phase synchrony of EEG oscillations, develops throughout the school years to support language comprehension in different ways depending on children's verbal and nonverbal skill levels.

KEYWORDS

children, EEG, language development, oscillations, phase synchrony, semantic unification

1 | INTRODUCTION

As we listen to speech, our ability to build a coherent and meaningful representation of what was said requires the seamless integration of activity from widely distributed brain areas, each specialized for processing different features of the input as they unfold over time (Hagoort, 2005). Dynamic functional connectivity, as measured

through changes in cross-trial phase synchronization of EEG oscillations over time, has been used to investigate the functional brain networks supporting many aspects of sensory and cognitive processing in adults (Fries, 2015; Siegel, Donner, & Engel, 2012; Singer, 2007); yet it has been underused to examine the brain networks supporting language comprehension, particularly in the developing brain. In fact, we know very little about the development of functional brain

network communication, even for relatively simple cognitive tasks (Maguire & Abel, 2013). A better understanding of the functional brain networks that are involved in unifying word meaning information during language comprehension – and how communication in these networks emerge with typical development – could provide new insights into the mechanisms of language processing and disorders.

Language comprehension is a fundamental cognitive skill that relies on multiple processes, each with different developmental trajectories (Skeide & Friederici, 2016). To understand speech, a listener must extract acoustic features and relate them to stored phonological forms, categorize word forms based on morphosyntactic, and lexical-semantic features, construct a phrase structure, retrieve word meanings, hold items online in working memory and, finally, unify all of this into an unfolding, sometimes multimodal, often novel, discourse representation so that a coherent understanding is achieved (Baggio & Hagoort, 2011; Hagoort, 2005; Skeide & Friederici, 2016). This relies on the coordinated activity of multiple neurocognitive processes communicating within a distributed cortical network (Salmelin & Kujala, 2006). In particular, dynamic interactions between superior/middle temporal gyrus ('Wernicke's area') and inferior frontal gyrus ('Broca's area') are considered to be key to so-called 'semantic unification' (i.e. activating stored lexical items and unifying them into novel representations) – an essential aspect of both language comprehension and production (Baggio & Hagoort, 2011). These cortical interactions may allow for top-down processing of semantic relationships – a higher level comprehension skill thought to emerge gradually throughout childhood and adolescence – although relatively little work has been done with children to know exactly when or how these skills, and their supporting brain networks, develop (Skeide & Friederici, 2016).

One way to measure the brain's functional interactions is to correlate the phase of EEG oscillations recorded from different electrodes. A consistent correlation is thought to reflect long-distance synchronization, and thus interaction and communication, among distributed brain regions, even if those regions are not physically connected (Fries, 2015; Siegel et al., 2012). Dynamic functional connectivity, as measured through changes in cross-trial phase synchronization over time, has been offered as a possible solution to the visual binding problem (i.e. how the brain integrates the processing of different object features, from different brain areas, into a unified visual representation; Fries, 2015; Rodriguez et al., 1999; Varela, Lachaux, Rodriguez, & Martinerie, 2001). In the same way, phase synchrony may also be a candidate mechanism for solving the so-called 'language-binding problem' (i.e. how the brain integrates linguistic information as it unfolds over time and is processed in specialized areas distributed throughout the brain; White et al., 2018).

Taking a network approach to neurolinguistic development differs from traditional approaches, one of which has been to use the N400 event related potential (ERP) component to track the neurocognitive basis of lexical-semantic development. The N400 is typically seen as an increased negativity in response to a semantic anomaly at midline/right central/parietal electrodes around

Research Highlights

- Functional brain network communication develops throughout the school years to support spoken language comprehension in different ways depending on children's verbal and nonverbal skills
- Children with stronger receptive vocabulary showed stronger phase synchrony of delta oscillations between right centroparietal and bilateral frontocentral electrodes while listening to well-formed sentences
- Younger children and those with weaker vocabulary skill may rely on compensatory integration of verbal and visual information to make sense of violation sentences
- Momentary changes in EEG phase synchrony indexes developmental changes to top-down semantic unification and nonverbal compensatory integration to extract meaning from spoken language

300–500 ms after stimulus onset. One prominent view is that it reflects the ease of lexical access as a function of the prior semantic context (Lau, Phillips, & Poeppel, 2008). N400-like negativities have been reported in infants as young as 14 months (Friedrich & Friederici, 2005), suggesting the basic mechanisms underlying the N400 become available from early stages of language development onwards. In children, however, the N400 effect tends to be larger in amplitude, longer in latency, and more broadly or frontally distributed compared to the short-lasting, focal posterior effect seen in adults (Atchley et al., 2006; Friedrich & Friederici, 2005; Hahne, Eckstein, & Friederici, 2004; Silva-Pereyra, Klarman, Lin, & Kuhl, 2005). Recently, Schneider and Maguire (2019) used a N400 paradigm to compare oscillatory power in children (aged 8–9), adolescents (aged 12–13) and adults while listening to correct sentences and sentences containing a semantic violation. They found greater theta (4–8 Hz) power at right frontal and central electrodes for semantic violations, which became more robust with age. In contrast, the N400, a time- and phase-locked evoked response, showed no age-related difference, suggesting oscillations/power may be a more sensitive metric of semantic development in school-aged children. Altogether, this suggests a developmental trajectory, beginning in infancy and continuing into adolescence, by which the ability to integrate semantic cues in a sentence to facilitate lexical access becomes increasingly efficient with age and experience.

Both ERPs and oscillatory power measure neurocognitive activity at particular electrodes, rather than the coordination of activity between electrodes. Thus, both reflect localized neurocognitive activity, rather than the dynamic interactions among brain structures that is the hallmark of language comprehension. Examining how the between-electrode phase synchronization of EEG oscillations differs between well-formed sentences and sentences containing a semantic violation would provide a more direct measure of the functional brain network communication that supports semantic unification.

To the best of our knowledge, no study has examined the development of oscillatory phase synchrony in children using a traditional N400 paradigm. Here we examine, for the first time, how the dynamic communication supporting semantic unification emerges with development. Building on relevant work with adults (Bastiaansen & Hagoort, 2015; Molinaro, Barraza & Carreiras, 2013; White et al., 2018), we predict that semantic unification will be disrupted when listening to sentences containing a semantic violation, and that this will be reflected by a decrease in oscillatory phase synchrony between frontal and posterior electrodes. We also predict that this pattern will be strongest in older children and those with more advanced vocabulary skill. Traditional indices of lexical-semantic access (i.e. N400s and low frequency oscillatory power, both measured as activity localized at particular electrodes rather than as synchronous activity between electrodes) will also likely become more robust with age (Hahne et al., 2004; Schneider & Maguire, 2019). Our participants range in age (4–17 years) and vocabulary skill level so we can associate individual differences in age, behaviour (standardized vocabulary test scores) and neurocognitive measures of semantic processing (ERPs, power, phase synchrony). As such, the current proof-of-concept study aims to complement what we know about the development of lexical/semantic retrieval/integration (as indexed by the N400) to better understand how semantic unification emerges with development.

2 | METHODS

2.1 | Participants

Twenty-six right-handed children (age 4 years 9 months–17 years 2 months; 14 females; Edinburgh Handedness Inventory), all native English speakers, participated in the study. Data from an additional child were collected but excluded from analysis due to recording problems. All had normal or corrected-normal vision, hearing and neurological health, and were in the age-appropriate grade at school. Participants and their parents provided informed consent and received a gift card as compensation. This study was approved by the Research Ethics Board at the Hospital for Sick Children.

2.2 | Stimuli

Stimuli were designed by the Brain Development Lab at the University of Oregon (described in Weber-Fox, Hampton Wray and Arnold, 2013). Participants watched four short animated movies (each approximately 6 min) on a laptop while listening, via headphones, to a narrator tell a corresponding story using natural speech. Each movie contained 100 simple sentences, which were embedded in an ongoing narrative and corresponded to the scene depicted in the video. All sentences were short (average 8 words), had subject-verb-object (SVO) structure, contained simple vocabulary, and were in the active voice. Sentences were either meaningful

and grammatically correct English sentences, contained an anomaly (semantic, phrase structure or subject-verb morphological agreement violation) or were spoken in Jabberwocky (all content words were replaced with pseudowords; see White et al., 2018); the order of sentence conditions was pseudorandomly distributed. Here, we analyze sentences that contained a semantic violation and their correct control counterparts (40 of each). Semantic violations were derived from correct sentences by replacing a noun with one that was semantically inappropriate with the sentence context (e.g. Pingu hits his fork/*cloud against the table; * marks the violation; critical words are underlined). Critical words always occurred in the middle of the sentence to avoid confounding sentence wrap-up effects. Two versions of each movie were counterbalanced across participants, so that a given sentence was correct in one version and contained a violation in the other, and no participant heard the same sentence twice. These sentence stimuli have been shown to elicit N400s in children (Weber-Fox, Wray, & Arnold, 2013).

2.3 | Psychometric tests

Receptive vocabulary was evaluated using the Peabody Picture Vocabulary Test-4 (PPVT; Dunn & Dunn, 2007). Expressive vocabulary and non-verbal reasoning abilities were measured using the vocabulary and matrix reasoning subtests of the Weschler Abbreviated Scale of Intelligence (WASI-II; Wechsler, 2002); WASI scores were not collected for three participants.

2.4 | Procedure

Most participants ($n = 20$) arrived for testing with a sibling or friend. One child was tested with EEG while the other completed the psychometric tests, and vice versa after a lunch break. During EEG recording, participants sat approximately 40 cm away from a laptop and listened to the stimuli through headphones (audio levels set by participant). Participants were asked to watch the movies and no response was required. EEG testing took approximately one hour.

2.5 | Data recording and preprocessing

Continuous EEG data were recorded from 64 electrodes (1,000 Hz sampling, 0.01–200 Hz filter, impedance $< 10k\Omega$, referenced to an electrode between Cz and CPz using a NeuroScan v4.5 Synamps2 (Compumedics). Vertical and horizontal eye movements were monitored with electrodes placed above/below the left eye and outer canthi. EEG was synchronized with critical word onsets by a trigger code sent from the stimulus presentation software (Presentation) to the EEG data acquisition software (Neuroscan) via a parallel port.

Data processing was done using the Fieldtrip toolbox in Matlab (Oostenveld, Fries, Maris, & Schoffelen, 2011). Data were low-pass filtered at 100 Hz, re-referenced to the common average, epoched into

individual trials relative to critical word onsets (-3 to 5 s), de-trended to remove slow-shifts, and downsampled to 500 Hz. Consistently noisy channels were visually identified and replaced with interpolated proximal channels. Artifact rejection involved excluding trials with amplitude > 200 μV , independent component analysis (ICA; Jung et al., 2000) to remove eye movement and heart artifacts, and when necessary, visual analysis to reject individual trials. This resulted in an average of 35 ($SD = 5$) trials for correct and 36 ($SD = 5$) for violation conditions, a difference that was not significant ($p > .10$).

2.6 | Exploring individual developmental differences

The goal of this study was to explore how processing differs when listening to semantically correct and violation sentences, and to relate these effects to children's age and developing vocabulary skill level. Analyzing ERPs and oscillatory power on the one hand, and phase synchrony on the other, indexes both localized neurocognitive activity (e.g. lexical-semantic access; Lau et al., 2008) and how synchronous this activity is across electrodes positioned around the head (e.g. semantic unification; Baggio & Hagorrt, 2011). To do so, we first conducted analysis of ERP, oscillatory power and phase synchrony across all children to identify when, at which electrodes (and at which frequency bands) effects differ between sentence types. Then we associated any resulting ERP, power and phase synchrony effects with children's age, and their receptive (PPVT) and expressive (WASI) vocabulary scores. For all analyses, the Pearson correlation coefficient (r) is reported as a measure of linear correlation between EEG effects and language ability; the coefficient of determination (R^2) from robust regression analyses are also reported to estimate the strength of outlier-resistant regression data fits ('Robust Regression', 2017). Finally, partial correlations that remove the contribution of non-verbal reasoning ability (WASI matrix reasoning scores) are also reported to reveal developmental differences in EEG effects that are specific to children's emerging vocabulary skills. Correlations and regressions are reported with $n = 23$, as WASI scores were not collected from three participants.

2.7 | Analysis of event related potentials

ERPs were averaged for each participant and sentence condition, relative to a 100 ms baseline that directly preceded critical word onsets. These were then grand-averaged across all participants by condition (correct/violation) and ERPs were identified. Statistical analyses were performed using FieldTrip's cluster-based permutation tests (Maris & Oostenveld, 2007). At each electrode, correct and violation sentences were compared across participants with a two-tailed paired t -test. All directly neighbouring electrodes that exceeded a significance level of $p < .05$ were grouped into clusters (minimum two electrodes required) and their t -statistics summed. This cluster-level statistic test was compared to a null distribution (created by calculating t -statistics from randomly partitioning the dataset $1,000$ times) that assumed no difference between sentence types. Any cluster-level test statistic that fell

in the ± 2.5 th percentile was considered significant. Significant positive clusters represent greater positive activity for violation sentences; vice versa for negative clusters. Permutation testing was applied to data averaged within 300 – 500 ms and 500 – 800 ms to explore N400 effects within the classic time windows that have been used in previous studies with children (Holcomb, Coffey, & Neville, 1992). Developmental differences were quantified by associating the mean amplitude of the N400 difference wave (violation – correct) at electrodes Fz, Cz, Pz between 300 – 500 ms and 500 – 800 ms with individual differences in age, receptive (PPVT) and expressive (WASI) vocabulary scores.

2.8 | Analysis of time frequency representations of power

Event-related changes in power for various frequency components of the EEG were computed using Morlet wavelets (5 cycle width, 3 SD Gaussian time window function) on single trials for each condition and sentence type. Power was analyzed between 1 – 80 Hz in 1 Hz and 50 ms steps, $+3$ to -5 s surrounding critical word onsets. For each condition, time-frequency representations of single trial data were averaged and expressed as an increase or decrease relative to the baseline decibel power (Cohen, 2014). We chose a more distant baseline interval of -500 to -200 ms to avoid artifacts that can arise in power analyses when responses that occur after critical word presentation become temporally smeared into a baseline that directly precedes critical word onset (Cohen, 2014).

As with the ERPs, statistical analyses for power were performed using cluster-based permutation testing, with two major differences. First, data were averaged into canonical bins, corresponding to delta (1 – 3 Hz), theta (4 – 7 Hz), alpha (8 – 13 Hz), beta (14 – 30 Hz), and gamma (31 – 80 Hz, with a notch filter at 60 Hz to remove power line interference). Second, we conducted analyses across a wider time frame (0 – 2 s) and evaluated cluster-level statistics formed by clustering neighbouring electrodes and adjacent time points, rather than averaging within time windows. We did this because so few previous studies have investigated power effects in children that we did not have strong a priori hypotheses regarding its time course and we did not want to miss potential effects that may occur outside of the traditional N400 time window. We chose a long-time range as auditory responses, particularly in children, may be temporally protracted, and few studies have investigated power modulations during sentence-embedded violations presented aurally, even in adults. Potential developmental changes were quantified by associating any power effects revealed by the cluster-based permutation tests with individual differences in age, receptive (PPVT) and expressive (WASI) vocabulary scores.

2.9 | Phase synchrony analysis

Trial-by-trial data from each participant were z -scored and filtered (bandpass FIR filter using a hamming window and whose order

depended on the maximum filter length of all frequencies) into canonical frequency bands: delta (1–3 Hz), theta (4–7 Hz), alpha (8–13 Hz), beta (14–30 Hz) and gamma (30–80 Hz; 60 Hz notch filter to remove power line interference). Phase estimates were obtained using the Hilbert transform. Phase synchrony was measured using the Phase Lag Index (PLI; Stam, Nolte, & Daffertshofer, 2007), computed using in-house scripts and FieldTrip (Oostenveld et al., 2011). PLI calculates cross-trial phase synchrony between electrodes, attenuating zero-phase correlations (i.e. phase-locked activity occurring at the same point in time). This mitigates spurious effects of volume conduction and is preferred for comparing the time course of phase synchrony between conditions using EEG (Cohen, 2014, 2015). Note, PLI is a measure of coordinated activity, but it does not imply a causal or directed relationship. For each participant this resulted in 64×64 electrode connectivity matrices at each millisecond time point, frequency band, and condition (correct/violation). PLI values were averaged across electrodes within 6 regions of interest (left frontal/central: F1, F3, FC1, FC3, C1, C3; midline frontal/central: Fz, FCz, Cz; right frontal/central: F2, F4, FC2, FC4, C2, C4; left central/posterior: CP1, CP3, P1, P3, PO3, PO5; midline central/posterior: CPz, Pz, POz; right central/posterior: CP2, CP4, P2, P4, PO4, PO6), to measure synchronous activity between a particular region and activity at all other electrodes (regional phase synchrony).

Differences in regional phase synchrony for correct versus violation sentences were evaluated (across all children) in two steps. First, for each frequency band and region, a running two-tailed paired *t*-test compared PLI values for correct versus violation sentences at each time point from -0.5 to 5 s. Second, we controlled for multiple comparisons by conducting a cluster-based permutation test (10,000 permutations across sentence types within each frequency band) to determine a duration threshold equivalent to $p < .05$ (Cohen, 2014). Condition differences in regional phase synchrony were considered significant if they lasted longer than the threshold. Finally, we visualized the distribution of specific electrode connections that drove regional connectivity effects, by plotting the strongest connections (mean PLI values within the time window) across all children (Hardmeier et al., 2014).

Developmental differences in two metrics of network communication (connectivity strength and degree) were evaluated within any time window that showed a significant regional phase synchrony difference between correct and violation sentences across all children. Connection *strength* was calculated for each participant by averaging the regional phase synchrony (PLI values) over the time window, and then taking a difference between conditions. Node *degree* measures how many connections exceed a pre-determined threshold value (Sporns, 2013). Degree was calculated for each participant by normalizing mean PLI values (dividing by an estimate of the standard deviation using bootstrap resampling across all participants). Any PLI_{norm} value that exceeded a threshold value of ± 2.58 (i.e. critical value in a two-tailed *z* test with $\alpha = 0.01$) was considered a suprathreshold connection (Kadis, Dimitrijevic, Toro-Serey, Smith, & Holland, 2016). Developmental differences were quantified by

associating participants' connectivity strength and degree with individual differences in age, receptive (PPVT) and expressive (WASI) vocabulary scores.

The data that support the findings of this study are available from the corresponding author upon reasonable request.

3 | RESULTS

3.1 | Psychometric tests

Receptive and expressive vocabulary and non-verbal reasoning (measured by the PPVT, and the verbal and matrix reasoning subtests of the WASI) tended, not surprisingly, to increase with age [age/PPVT: $r(25) = 0.89$, $p < .001$; age/WASIV: $r(22) = 0.84$, $p < .001$; age/WASImr: $r(22) = 0.69$, $p < .001$]. However, the youngest and oldest participants did not always show the lowest and highest test scores, highlighting how individual differences in vocabulary and age relate differently to the neurocognitive mechanisms involved in semantic processing. Raw scores ranged from 90 to 214 (PPVT); 13–42 (WASI verbal) and 8–28 (WASI matrix reasoning). Using the conversion tables in the testing manuals, this translates to age-equivalences that range from 5;7 to +24;11 years;months for PPVT, and 6;2 – 29 + years;months for WASI verbal and nonverbal reasoning.

3.2 | ERPS

Figure 1 displays ERP plots and topological maps. A broadly distributed negativity is seen across all children, although it is longer lasting and extends more frontally than N400s typically reported in adults. Indeed, cluster-based permutation tests conducted within 300–500ms and 500–800 ms revealed a significant negative cluster for each time window (max sum = -31.62 , $p \leq .005$; max sum = -50.78 , $p < .001$, respectively) that were most prominent at midline central electrodes, but also extended frontally.

Developmental differences were explored by correlating and regressing the N400 difference wave at electrodes Fz, Cz and Pz with age and receptive and expressive vocabulary to explore how the distribution may differ across development. The effect at frontal Fz between 300–500 ms showed a moderate positive correlation (was smaller) with age [$r(22) = 0.47$, $p = .024$; $R^2 = 0.19$, $p_{rob} = .04$] and receptive vocabulary [PPVT: $r(22) = 0.46$, $p = .029$; $R^2 = 0.21$, $p_{rob} = 0.026$]. These relationships remained significant even when controlled for nonverbal reasoning [age: $r(22) = 0.43$, $p = .044$; PPVT: $r(22) = 0.45$, $p = .038$], indicating that the frontal N400 effect tended to be larger for younger children and those with weaker receptive vocabulary. This frontal effect was also somewhat longer lasting in younger children. This was suggested by trend towards a correlation between age and the Fz N400 effect between 500–800 ms [age: $r(22) = 0.40$, $p = .059$; $R^2 = 0.15$, $p_{rob} = 0.071$]. The correlation with vocabulary was not significant [PPVT; WASIV $p > .10$], and none of the correlations in this time window remained significant when we

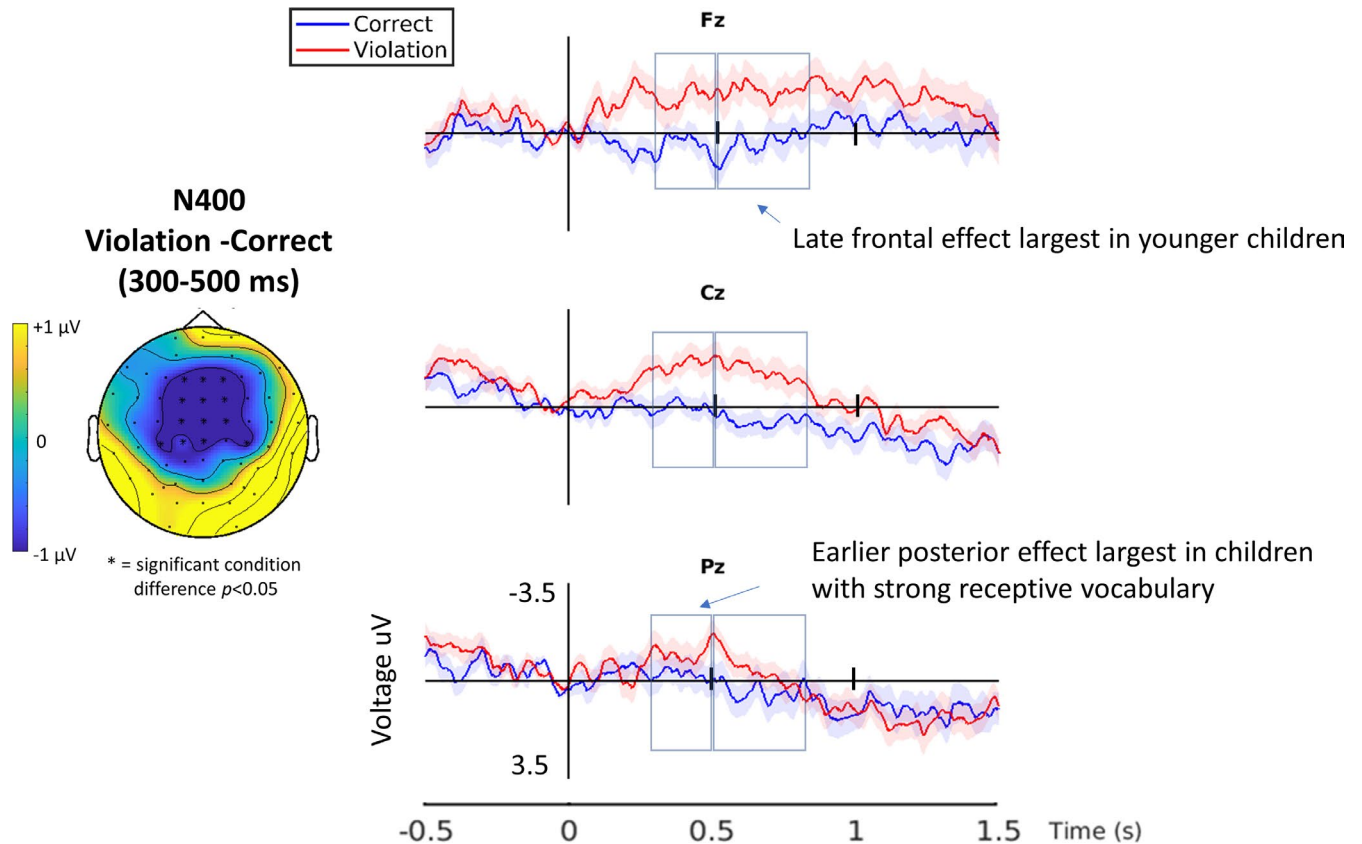


FIGURE 1 ERP effects. This figure shows the grand average event related potential (ERP) effects of all children over time at electrodes Fz, Cz, and Pz. ERPs are plotted from 500 ms before to 1,500 ms after critical word onsets while children listened to correct (blue) and violation (red) sentences (standard errors are indicated with shaded lines). Note negative is plotted up. Cluster-based permutation tests were run within 300–500 ms and 500–800 ms (indicated with a blue box) on the ERP plots. The head map displays the distribution of significant N400 effects across all children between 300–500 ms. The later frontal N400 effect was largest in younger children [$r(25) = 0.45, r < 0.05$]

controlled for nonverbal reasoning [age: $r(22) = 0.37, p = .091$; PPVT and WASIV $p > .10$].

There was some indication of a larger central and posterior N400 between 300 and 500 ms in children with stronger receptive vocabulary, as revealed by the robust regression analyses [Cz-PPVT: $r(22) = -0.39, p = .068; R^2 = 0.24, p_{rob} = .018$; Pz-PPVT: $r(22) p > .1; R^2 = 0.43, p_{rob} < .001$; Cz-age and Pz-age $p > .1$]. This trend persisted at Pz in the partial correlation that controlled for nonverbal reasoning [Pz:PPVT: $r(22) = -0.38, p = .078$; Cz:PPVT, Cz:age and Pz:age: $p > .10$]. No significant associations between age or vocabulary were found for N400 effects at Cz or Pz in the later time window.

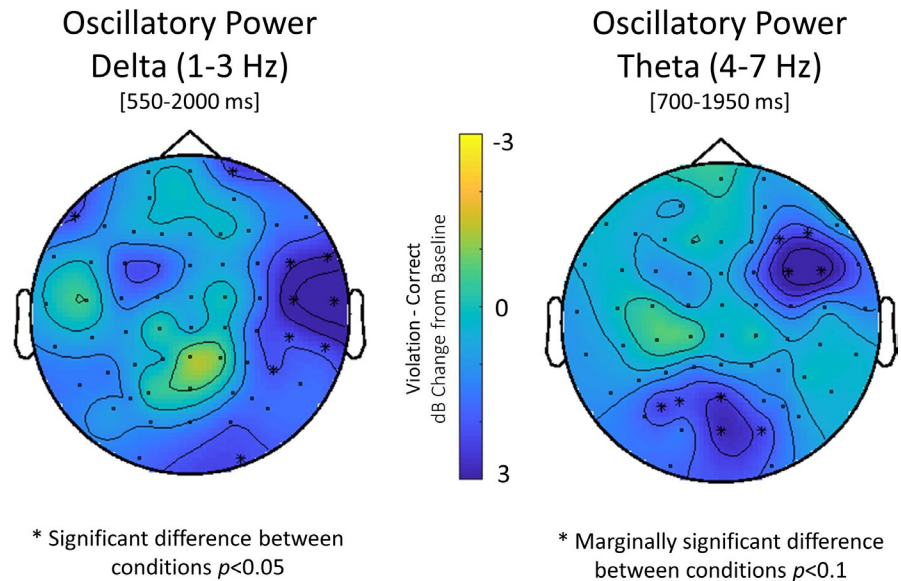
Together, this suggests that from early childhood to late adolescence, children show an N400 in response to semantic violations that tends to be largest at central electrodes. With development, this effect becomes more concentrated in time (300–500 ms) and distribution (centroparietal electrodes). That is, the N400 effect extends to frontal electrodes in younger children and those with weaker receptive vocabulary skill and tends to persist longer there in younger children. Children with stronger receptive vocabulary, in contrast, show some indication of a larger effect at central/posterior electrodes between 300 and 500 ms only.

3.3 | Oscillatory power

Figure 2 shows results of cluster-based permutation tests conducted to compare oscillatory power in correct versus violation sentences. Although tests were run on multiple frequency bands, condition differences were observed in lower frequencies only. Within delta (1–3 Hz), the permutation test revealed a long-lasting significant positive cluster between 0.55 and 2 s (max sum = 597.61, $p < .05$), indicating significantly greater delta band activity for violation sentences across all children. This cluster was most prominent at right-lateralized central electrodes (FT8, T8, PT8, FC6, C6, CP6, P6). Within theta (4–7 Hz), marginally significant positive clusters were seen between 700 ms–1.95 s (max sum = 210.8, $p < .10$) and 950 ms–1.75 s (max sum = 180.3, $p < .10$), most prominent at right frontocentral (F4, F6, FC4, FC6) and left/midline parietal (Pz, POz, PO4, P1, P3) electrodes. Analysis of other frequency bands revealed no significant effects ($p > .1$).

Developmental differences were explored by correlating/regressing condition differences in these power effects at electrodes involved in the clusters with age and vocabulary skill. No significant association were observed for either frequency band, suggesting these effects were relatively stable across development.

FIGURE 2 Oscillatory power effects. This figure shows the results of the cluster-based permutation tests that were conducted between 0 and 2 s to investigate condition differences in oscillatory power across all children. Results are shown for delta (1–3 Hz) and theta (4–7 Hz), which showed significant ($p < .05$) and marginally significant ($p < .10$) condition differences, respectively. Topographical head maps show the distribution of power effects (dB power relative to baseline; clusters are indicated by *; blue indicates effects that are larger for the violation sentences). Correlations with these effects and children's age and language skills did not reveal significant developmental differences



No significant developmental differences observed

3.4 | Phase synchrony

Two significant regional phase synchrony effects were seen across all children, both involving oscillations recorded from right central/posterior electrodes (CP2, CP4, P2, P4, PO4, PO6) and both in the delta frequency band (Figure 3). The first was significantly *greater* phase synchrony for correct sentences between 1.27 and 1.53s ($p_{\text{corr}} < .05$). The strength of this effect was positively correlated with both receptive and expressive vocabulary scores [PPVT: $r(22) = 0.50$, $p = .02$; $R^2 = 0.24$, $p_{\text{rob}} = .02$; WASIv: $r(22) = 0.46$, $p = .03$; $R^2 = 0.21$, $p_{\text{rob}} = .03$, respectively]. The relationship between receptive vocabulary and connectivity strength remained significant even when we controlled for nonverbal reasoning [PPVT: $r(22) = 0.43$, $p = .04$; WASIv: $r(22) = 0.35$, $p > .1$]. Thus, children with stronger vocabulary skills showed a stronger connectivity effect (i.e. more phase synchrony for correct sentences) in this time window. There was some indication that stronger vocabulary also related to more network connections: vocabulary and age were correlated with mean network degree, particularly in the outlier-resistant robust regression model [PPVT: $r(22) = 0.35$, $p = .10$; $R^2 = 0.25$, $p_{\text{rob}} = 0.02$; WASIv: $r(22) = 0.28$, $p > .1$; $R^2 = 0.26$, $p_{\text{rob}} = 0.01$; Age: $r(22) = 0.26$, $p > .1$; $R^2 = 0.25$, $p_{\text{rob}} = .01$]. However, these relationships were not significant when we controlled for nonverbal reasoning skill ($ps > .1$). In terms of the distribution of this effect, the phase of oscillations from right central/posterior electrodes was most synchronous with oscillations at bilateral frontal/central electrodes.

The second regional phase synchrony effect occurred between 3.41 and 3.64 s. It also involved right central/parietal electrodes and oscillations in the delta frequency band effect; however, it was reversed, showing significantly *less* phase synchrony for correct compared to violation sentences ($p_{\text{corr}} < 0.05$). Although the strength of this effect did not show a relationship with age or vocabulary ($ps > 0.1$), the number of connections *decreased* with development: mean network degree was *negatively* correlated with age

and vocabulary, particularly in the outlier-resistant robust regression model [age: $r(22) = -0.42$, $p = .06$; $R^2 = 0.24$, $p_{\text{rob}} = 0.02$; PPVT: $r(22) = -0.40$, $p = .06$; $R^2 = 0.24$, $p_{\text{rob}} = .02$; WASIv: $r(22) = -0.38$, $p = .07$; $R^2 = 0.23$, $p_{\text{rob}} = 0.02$]. These relationships were not significant when we control for nonverbal matrix reasoning, suggesting this effect was not specific to language skill [age: $r(22) = -0.32$, $p > .1$; PPVT: $r(22) = -0.33$, $p > .1$; WASIv: $r(22) = -0.30$, $p > .1$]. In fact, mean network degree also showed a negative relationship with non-verbal reasoning, particularly in the outlier-resistant robust regression model, suggesting this effect was driven in part by children's visual-spatial skills [WASIv: $r(22) = -0.38$, $p = .07$; $R^2 = 0.23$, $p_{\text{rob}} = .02$]. In terms of the distribution, in this time window the phase of oscillations from right central/posterior electrodes was most synchronous with frontal right/midline electrodes.

In all other frequency bands and regions analyzed we saw evidence from the running *t*-test of brief intervals in which there was a difference between correct and violation sentences; however, these effects were not robust enough to pass the multiple comparison control.

Figure 3 shows the time series of regional phase synchrony (PLI values) of right central/posterior electrodes in the delta frequency band from the onset of the critical word in correct and violation sentences across all children; head-maps display the electrode-electrode connections that contributed most to the two significant effects. Figure 4 shows scatter plots of the relationship between connectivity strength and receptive and vocabulary scores in the early time window.

4 | DISCUSSION

This is the first study to identify developmental differences in the phase synchronization of EEG oscillations during lexical/semantic

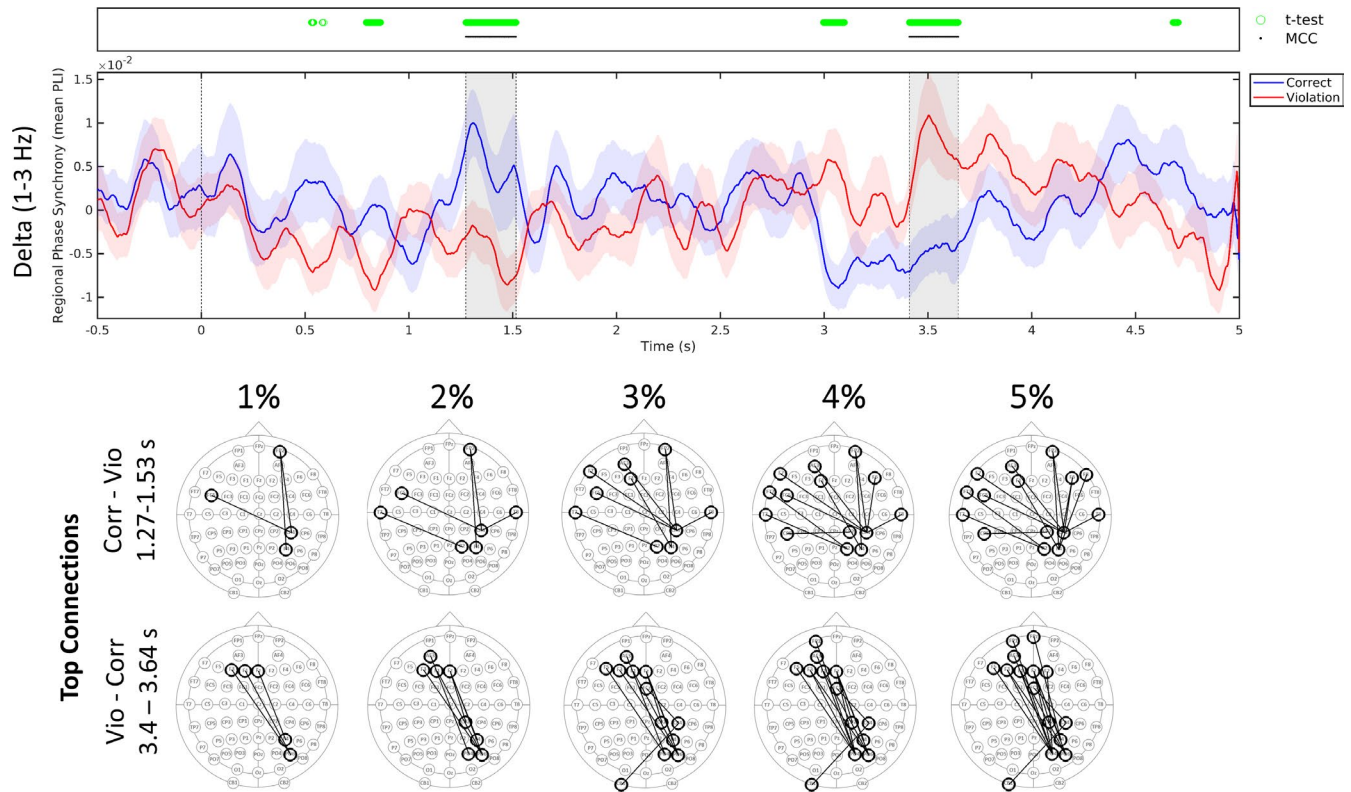


FIGURE 3 Phase Synchrony of Delta Oscillations from Right Central/Parietal Electrodes over Time. This figure shows the time series of regional phase synchrony (mean PLI values) of right central/posterior electrodes in the delta frequency band (1–3 Hz) from 500 ms before the onset of the critical word in correct (blue) and violation (red) sentences across all children (standard errors are indicated with shaded lines). Results of the running *t*-tests that compare regional phase synchrony PLI values for correct versus violation sentences at each time point are presented above the figure as green circles ($p < .05$); values that passed the multiple comparison control (MCC) are shown as small black circles ($p_{corr} < .05$) and highlighted with a shaded box. Head-maps display the top electrode connections that contributed most to the two significant effects across children.

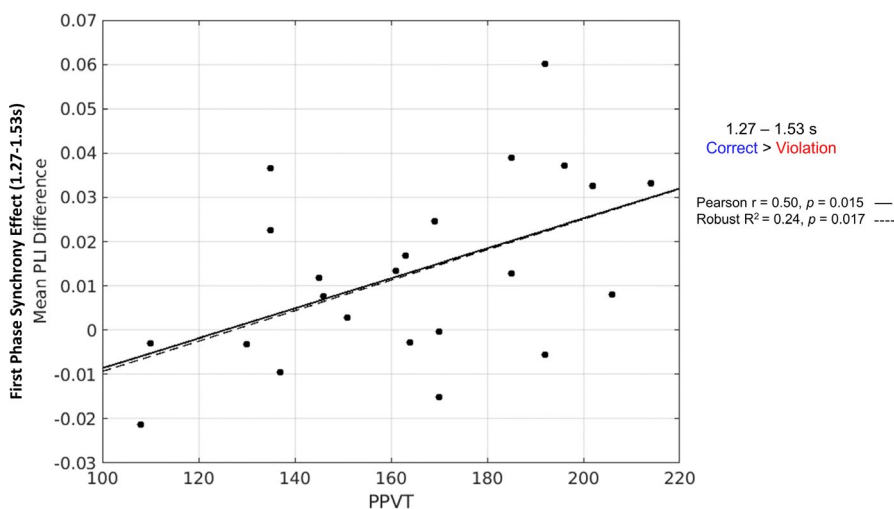


FIGURE 4 Relationship between Functional Brain Network Strength and Individual Differences in Vocabulary Skill. This figure shows a scatter plot of the relationship between children's receptive vocabulary skill (Picture Peabody Vocabulary Test, PPVT scores) and the regional phase synchrony effect (connectivity strength correct > violation sentences) between 1.27–1.53 s [$r(22) = 0.50, p = .02; R^2 = 0.24, p = .02$]. This relationship remained significant even when controlling for nonverbal reasoning [$r(22) = 0.43, p = .04$].

aspects of sentence processing. This is important because it allows us to examine how the brain may coordinate its activity across different regions to support semantic unification, and how this process differs depending on children's age and language skill level. Additionally, we explored how ERPs and oscillatory power (both measures of localized neurocognitive activity) differ across development to contextualize

our phase synchrony findings. We found that children with more advanced vocabulary showed stronger phase synchrony between right central/posterior and bilateral frontal/central electrodes in the delta frequency band when listening to well-formed sentences compared to those containing a semantic violation (1.27–1.53 s after critical word onset). We suggest this indicates greater recruitment

of the functional brain networks important for top-down semantic unification with increasing vocabulary skill. In contrast, younger children and those with less-developed vocabulary showed a later, reversed effect (more synchrony for violation sentences). This may indicate greater reliance on nonverbal compensatory processing to exact meaning from spoken language. We suggest that functional brain network communication, as measured by both localized phase-locked N400 activity as well as momentary changes in the phase synchrony of distributed EEG oscillations, continues to develop throughout the school years to support language comprehension. We now discuss these findings, starting with ERPs and oscillatory power, and then our earlier and later phase synchrony effects.

Consistent with previous studies (e.g. Hahne et al., 2004), we found age-related differences in the distribution and duration of the N400 effect observed while children listened to sentence-embedded semantic violations versus correct sentences. Stronger receptive vocabulary skill was also associated with an N400 that was concentrated in time (300–500 ms) and distribution (central/posterior electrodes). This contrasts with the findings of some (Henderson, Baseler, Clarke, Watson, & Snowling, 2011), but not all (Khalifian, Stites, & Laszlo, 2016) of the few previous studies that relate individual differences in vocabulary skill with children's N400 responses. It may be that testing participants from a wide range of age and skill levels studies (as in the current study) provided the necessary variance to fully appreciate this brain-behaviour association. Our findings suggest that the lexicosemantic retrieval processes that are thought to be reflected by the N400 become more localized to centroparietal electrodes, and perhaps more efficient, with age and receptive vocabulary development.

Children also showed greater low frequency oscillatory power while listening to sentence-embedded semantic violations compared to correct, meaningful sentences. Condition differences were significant in delta (1–3 Hz) across a long time-window (550–2000 ms) and were most prominent at right-lateralized central electrodes. A trend towards significance was also seen in theta (3–7 Hz) between 700–1950 ms at right frontocentral and left/midline parietal electrodes. To our knowledge only one other study has examined oscillatory power while children listen to well-formed sentences compared to sentence-embedded semantic violations, and it also reports greater low frequency oscillations at right frontocentral electrodes for violation sentences in children (8–9 years), adolescents (12–13 years), and adults (Schneider & Maguire, 2019). Note that in Schneider and Maguire, analyses were restricted to a narrow time/frequency window (only theta effects between 350–550 ms), so it is unknown whether longer lasting or lower frequency effects might have also been present. In adults, greater theta power for sentence-embedded semantic violations (compared to correct sentences) is a consistent finding that has been linked to lexical-semantic retrieval (Bastiaansen & Hagoort, 2015), as well as to domain-general working memory demands (e.g. the temporal integration of cell assemblies to organize sequential items in working memory's phonological loop; Roux & Uhlhass, 2014). Future studies that relate individual differences in children's language versus working memory to oscillatory

power effects may help tease these possibilities apart. In this study, we did not find consistent developmental differences in power effects, which may suggest they are relatively stable across the developmental range studied here. It is worth noting that our analysis of total power included both evoked and induced power (oscillations that were and were not phase-locked to stimulus onset). It may be that it is specifically phase-aligned neural activity that emerges later in development, which would explain our finding of developmental differences in ERPs (phase-locked to stimulus onset) and phase synchrony (between-electrode phase-alignment), but not in total power effects. Alternatively, more participants may contribute necessary statistical power. Future studies comparing developmental trajectories of induced versus evoked power during sentence processing would help elucidate possible developmental mechanisms further.

Our novel contribution to the literature is that children showed greater oscillatory phase synchrony when listening to well-formed sentences compared to sentences containing a semantic violation. This effect related specifically to individual differences in children's vocabulary skill level: it was stronger in children with more advanced receptive vocabulary, and this relationship remained significant even after controlling for non-verbal reasoning ability. The direction of our effect (greater phase synchrony during meaningful language comprehension) as well as its distribution (right centroparietal to frontocentral;) corroborates the findings of previous work with adults. For example, White et al. (2018) report greater EEG phase synchrony between posterior and frontal/central electrodes when adults listen to meaningful compared to meaningless Jabberwocky sentences (in which content words were replaced with pseudowords and no semantic representation could be built). Similarly, Molinaro, Barraza, and Carreiras (2013) report greater EEG phase synchrony between right frontal-occipital electrodes when adults read a word that was expected within the previous semantic context, compared to one that was not. We now extend this to show a similar pattern in children while they listened to well-formed sentences compared to sentences containing a semantic violation. Furthermore, our correlation results suggest that this dynamic functional network communication emerges with development and its strength relates specifically to children's increasing vocabulary skill throughout the school-aged years.

While the poor spatial resolution of EEG analysis cautions us against linking particular brain sources with our pattern of phase synchrony, one could speculate how the distribution of our phase synchrony effects may be consistent with both a semantic unification perspective (Baggio & Hagoort, 2011), as well as contemporary models of language development (Skeide & Friederici, 2016). Across all children, oscillations recorded from right central/parietal electrodes showed greater phase synchrony for correct compared to violation sentences. The N400 in adults is typically reported here, even though source localization points to generators in mid/posterior portions of the left temporal cortex (Lau et al., 2008), where word meaning and phonological form are understood to be represented from early stages of language acquisition onwards (Skeide & Friederici, 2016). We found that this right central/posterior activity

was synchronous with oscillations at frontal/central electrodes. This may reflect functional connections between activity in (left) temporal and bilateral inferior frontal brain areas, which are thought to be important for retrieving word meanings from memory and unifying them into the context of the sentence, respectively (Zhu et al., 2012). Left temporal and inferior frontal connections are assumed to support the development of skilled top-down processing of semantic relationships, but until now this has been studied primarily in adults (Skeide & Friederici, 2016; although see Youssofzadeh, Vannest, & Kadis, 2018, for the recent finding of more functional connections between these areas among adolescents versus young children as measured with fMRI and during a verb generation task). Our findings may add to this and provide support for the gradual emergence of these top-down semantic unification processes throughout the school-age years, even when listening to relatively simple sentences. Future work using MEG or analysis of EEG phase synchrony conducted after source localization will be important to further explore the functional selectivity of frontal-temporal connections and how its development relates to skilled and efficient language comprehension. Additionally, future work could explore the direction of information flow with directed measures of phase synchrony, such as Granger causality.

In contrast to studies with adults, which link semantic unification to EEG synchronization in high frequency gamma bands (30 Hz+; Bastiaansen & Hagoort, 2015; Molinaro et al., 2013; White et al., 2018), the effects we observe here in children occurred in very slow delta frequency band (1–3 Hz). This corroborates the results of the few other relevant studies that have been conducted with school-aged children and is also consistent with our power effects. For example, during word reading, typically developing children show greater increases in delta (1–6 Hz) power compared to age-matched children with a diagnosed learning disability (Fernández et al., 2012). Age-related differences in EEG theta (4–6 Hz) power during semantic violation processing (Schneider & Maguire, 2019) and in MEG theta phase synchronization during an expressive language task (Doesburg, Tingling, MacDonald, & Pang, 2016) have also been reported (theta was the lowest frequency reported in both studies). Schneider, Abel, Ogiela, McCord, and Maguire (2018) also report that during the course of (well-formed) sentence comprehension, 10–12 year-old children show greater changes in theta power, whereas adults show greater changes in higher frequency beta power. Even at rest EEG power spectra shows age-dependent changes across childhood, and in particular is dominated by slower frequency oscillations in younger compared to older children and adolescents (Clarke, Barry, McCarthy, & Selikowitz, 2001; Cragg et al., 2011). Although not yet fully understood, this pattern may reflect a decline in gray matter volume (related to 'synaptic pruning'), increase in white matter volume (related to myelination of axons), or changes to neurotransmitter levels, all of which increase the efficiency of neural firing and are known to continue changing well into adolescence, particularly in brain areas important for language (Segalowitz, Santesso, & Jetha, 2010). For whatever reason, neurons appear to spontaneously oscillate at a slower rate in children and

adolescents compared to adults, and so brain network communication may also occur via slower-moving oscillations by 'riding on the wave' of the dominant rhythm (, Rothenberger, 2009). This underscores why developmental models of neuronal communication cannot be simply inferred from adult data. More work will be needed to pinpoint when in development the frequency of communication becomes more adult-like.

How can we integrate our ERP, power and phase synchrony findings? For one thing, phase synchrony effects occurred much later than the N400 (1.27–1.53 s after critical word onset for the first phase synchrony effect). However, given delta's low frequency, this means phase synchrony was modulated after only 1–3 cycles of oscillations. Additionally, while we observed an increase in ERP and power effects for violation sentences, phase synchrony was greater for correct sentences. One way to interpret these findings is that, when encountering a word that was not expected in the prior sentence context, more resources were required to retrieve the representation of that word from lexical memory. This was associated with an N400 response in all children that was more concentrated in time and distribution in older/more skilled children. This may then have led to more neurons oscillating at slow frequencies (power increase), and to a disruption in the synchronous timing of slow frequency oscillations across the brain (which was seen when children listened to meaningful sentences). Interestingly, different electrodes showed oscillatory power and phase synchrony effects but only the phase synchrony effect correlated with children's vocabulary skill level. A similar dissociation between local oscillatory activity (power) and long-range synchronization has been reported previously (e.g. Hipp, Engel, & Siegel, 2011; White et al., 2018) and may indicate that the coordination of distributed frequency-specific neuronal activity may occur independently to changes in the amount of local neuronal activity, and vice versa. Importantly, that children with stronger receptive vocabulary showed a N400 that was more concentrated to centroparietal electrodes and greater disruption in the phase synchrony of oscillations recorded at this area, suggests that it is the coordinated timing of neural activity that is most sensitive to developmental differences in language skill.

Finally, our second phase synchrony effect occurred much later (around 3.5 s, or 3–10 cycles of oscillations) and in the opposite direction, showing greater phase synchrony for violation compared to correct sentences. This later effect decreased with development – it involved fewer connections in older children and those with more advanced vocabulary skill. Moreover, it appeared to depend in part on children's nonverbal reasoning skill, because unlike our first effect, it did not remain significant in the partial correlation analysis when the variance due to matrix reasoning skill was removed. Similarly, these were the same children that tended to show a prolonged N400 effect. This late effect may index a compensatory re-evaluation strategy, which these children initiated towards the end of the sentence. For example, they may have attempted to make sense of the violation sentences by integrating what they saw in the movie with what they heard



spoken by the narrator (e.g. listening to 'He eats more toy than he did yesterday' when viewing Pingu sitting at the table eating food). Indeed, even very young children use visual contextual information to facilitate spoken language comprehension (Vigliocco, Perniss & Vinson, 2014). It may be that our later effect is tapping into such multimodal integration processes.

In conclusion, our findings suggest that functional brain network communication continues to develop throughout the school years to support language comprehension, and it may do so in different ways depending on children's verbal and nonverbal skill level. Children with stronger receptive vocabulary showed stronger phase synchrony of delta oscillations between right central/posterior and frontal/central electrodes while listening to well-formed sentences compared to sentences containing a semantic violation. Younger children and those with weaker vocabulary skill may rely more on their nonverbal reasoning abilities to make sense of violation sentences. We suggest that with development comes greater top-down semantic unification and reduced reliance on nonverbal compensatory integration to exact meaning from spoken language. Phase synchrony of EEG oscillations during speech may provide a sensitive tool for studying how functional brain network communication emerges with development, and how it may vary for different populations of children.

ACKNOWLEDGEMENTS

This research was supported by EpLink, in partnership with the Ontario Brain Institute. The authors thank Eric Pakulak and Mandy Hampton Wray for sharing stimuli, Grace Sim and Anne Keller for programming our analysis pipelines, Candace Nayman and Alexandra Mogadam for helping with data acquisition, as well as our participants and families.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author (Erin J. Panda; epanda@brocku.ca) upon reasonable request.

REFERENCES

- Atchley, R. A., Rice, M. L., Betz, S. K., Kwasny, K. M., Sereno, J. A., & Jongman, A. (2006). A comparison of semantic and syntactic event related potentials generated by children and adults. *Brain and Language*, 99(3), 236–246 <https://doi.org/10.1016/j.bandl.2005.08.005>
- Baggio, G., & Hagoort, P. (2011). The balance between memory and unification in semantics: A dynamic account of the N400. *Language and Cognitive Processes*, 26(9), 1338–1367 <https://doi.org/10.1080/01690965.2010.542671>
- Bastiaansen, M., & Hagoort, P. (2015). Frequency-based segregation of syntactic and semantic unification during online sentence level language comprehension. *Journal of cognitive neuroscience*, 27(11), 2095–2107 https://doi.org/10.1162/jocn_a_00829

- Clarke, A. R., Barry, R. J., McCarthy, R., & Selikowitz, M. (2001). Age and sex effects in the EEG: Development of the normal child. *Clinical Neurophysiology*, 112(5), 806–814 [https://doi.org/10.1016/S1388-2457\(01\)00488-6](https://doi.org/10.1016/S1388-2457(01)00488-6)
- Cohen, M. X. (2014). *Analyzing Neural Time Series Data: Theory and Practice*. Cambridge, Massachusetts: MIT Press
- Cohen, M. X. (2015). Effects of time lag and frequency matching on phase-based connectivity. *Journal of Neuroscience Methods*, 250, 137–146 <https://doi.org/10.1016/j.jneumeth.2014.09.005>
- Cragg, L., Kovacevic, N., McIntosh, A. R., Poulsen, C., Martinu, K., Leonard, G., & Paus, T. (2011). Maturation of EEG power spectra in early adolescence: A longitudinal study. *Developmental Science*, 14(5), 935–943 <https://doi.org/10.1111/j.1467-7687.2010.01031.x>
- Doesburg, S. M., Tingling, K., MacDonald, M. J., & Pang, E. W. (2016). Development of network synchronization predicts language abilities. *Journal of Cognitive Neuroscience*, 28(1), 55–68 https://doi.org/10.1162/jocn_a_00879
- Dunn, L. M., & Dunn, D. M. (2007). *PPVT- 4: Peabody picture vocabulary test*. Minneapolis, MN: Pearson Assessments
- Fernández, T., Harmony, T., Mendoza, O., López-Alanís, P., Marroquín, J. L., Otero, G., & Ricardo-Garcell, J. (2012). Event-related EEG oscillations to semantically unrelated words in normal and learning disabled children. *Brain and Cognition*, 80(1), 74–82 <https://doi.org/10.1016/j.bandc.2012.04.008>
- Friedrich, M., & Friederici, A. D. (2005). Lexical priming and semantic integration reflected in the event-related potential of 14-month-olds. *NeuroReport*, 16(6), 653–656 <https://doi.org/10.1097/00001756-200504250-00028>
- Fries, P. (2015). Rhythms for cognition: Communication through coherence. *Neuron*, 88(1), 220–235 <https://doi.org/10.1016/j.neuron.2015.09.034>
- Hagoort, P. (2005). On Broca, brain, and binding: A new framework. *Trends in Cognitive Sciences*, 9(9), 416–423 <https://doi.org/10.1016/j.tics.2005.07.004>
- Hahne, A., Eckstein, K., & Friederici, A. D. (2004). Brain signatures of syntactic and semantic processes during children's language development. *Journal of Cognitive Neuroscience*, 16(7), 1302–1318 <https://doi.org/10.1162/0898929041920504>
- Hardmeier, M., Hatz, F., Bousleiman, H., Schindler, C., Stam, C. J., & Fuhr, P. (2014). Reproducibility of functional connectivity and graph measures based on the phase lag index (PLI) and weighted phase lag index (wPLI) derived from high resolution EEG. *PLoS ONE*, 9(10) <https://doi.org/10.1371/journal.pone.0108648>
- Henderson, L. M., Baseler, H. A., Clarke, P. J., Watson, S., & Snowling, M. J. (2011). The N400 effect in children: Relationships with comprehension, vocabulary and decoding. *Brain and Language*, 117(2), 88–99 <https://doi.org/10.1016/j.bandl.2010.12.003>
- Hipp, J. F., Engel, A. K., & Siegel, M. (2011). Oscillatory synchronization in large-scale cortical networks predicts perception. *Neuron*, 69(2), 387–396 <https://doi.org/10.1016/j.neuron.2010.12.027>
- Holcomb, P. J., Coffey, S. A., & Neville, H. J. (1992). Visual and auditory sentence processing: A developmental analysis using event-related brain potentials. *Developmental Neuropsychology*, 8(2–3), 203–241 <https://doi.org/10.1080/87565649209540525>
- Jung, T. P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., & Sejnowski, T. J. (2000). Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. *Clinical Neurophysiology*, 111(10), 1745–1758 [https://doi.org/10.1016/S1388-2457\(00\)00386-2](https://doi.org/10.1016/S1388-2457(00)00386-2)
- Kadis, D. S., Dimitrijevic, A., Toro-Serey, C. A., Smith, M. L., & Holland, S. K. (2016). Characterizing information flux within the distributed pediatric expressive language network: A core region mapped through fMRI-constrained MEG effective connectivity analyses. *Brain Connectivity*, 6(1), 76–83 <https://doi.org/10.1089/brain.2015.0374>

- Khalifian, N, Stites, M. C, & Laszlo, S (2016). Relationships between event-related potentials and behavioral and scholastic measures of reading ability: A large-scale, cross-sectional study. *Developmental Science*, 19(5), 723–740 <https://doi.org/10.1111/desc.12329>
- Lau, E. F, Phillips, C, & Poeppel, D (2008). A cortical network for semantics:(de) constructing the N400. *Nature Reviews Neuroscience*, 9(12), 920 <https://doi.org/10.1038/nrn2532>
- Maguire, M. J, & Abel, A. D (2013). What changes in neural oscillations can reveal about developmental cognitive neuroscience: Language development as a case in point. *Developmental Cognitive Neuroscience*, 6, 125–136 <https://doi.org/10.1016/j.dcn.2013.08.002>
- Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG-and MEG-data. *Journal of neuroscience methods*, 164(1), 177–190.
- Molinaro, N, Barraza, P, & Carreiras, M (2013). Long-range neural synchronization supports fast and efficient reading: EEG correlates of processing expected words in sentences. *NeuroImage*, 72, 120–132 <https://doi.org/10.1016/j.neuroimage.2013.01.031>
- Oostenveld, R, Fries, P, Maris, E, & Schoffelen, J (2011). FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, 2011, 1 <https://doi.org/10.1155/2011/156869>
- Robust regression. (2017). Retrieved from: <https://www.mathworks.com/help/stats/robustfit.html?requestedDomain=true>
- Rodriguez, E, George, N, Lachaux, J.-P, Martinerie, J, Renault, B, & Varela, F. J (1999). Perception's shadow: Long-distance synchronization of human brain activity. *Nature*, 397(6718), 430 <https://doi.org/10.1038/17120>
- Rothenberger, A (2009). Brain oscillations forever—neurophysiology in future research of child psychiatric problems. *Journal of Child Psychology and Psychiatry*, 50(1–2), 79–86 <https://doi.org/10.1111/j.1469-7610.2008.01994.x>
- Roux, F, & Uhlhaas, P. J (2014). Working memory and neural oscillations: Alpha–gamma versus theta–gamma codes for distinct WM information? *Trends in Cognitive Sciences*, 18(1), 16–25 <https://doi.org/10.1016/j.tics.2013.10.010>
- Salmelin, R, & Kujala, J (2006). Neural representation of language: Activation versus long-range connectivity. *Trends in Cognitive Sciences*, 10(11), 519–525 <https://doi.org/10.1016/j.tics.2006.09.007>
- Schneider, J, Abel, A, Ogiela, D, McCord, C, & Maguire, M (2018). Developmental differences in the neural oscillations underlying auditory sentence processing in children and adults. *Brain and Language*, 186, 17–25 <https://doi.org/10.1016/j.bandl.2018.09.002>
- Schneider, J. M, & Maguire, M. J (2019). Developmental differences in the neural correlates supporting semantics and syntax during sentence processing. *Developmental Science*, 22(4), e12782 <https://doi.org/10.1111/desc.12782>
- Segalowitz, S. J, Santesso, D. L, & Jetha, M. K (2010). Electrophysiological changes during adolescence: A review. *Brain and Cognition*, 72(1), 86–100 <https://doi.org/10.1016/j.bandc.2009.10.003>
- Siegel, M, Donner, T. H, & Engel, A. K (2012). Spectral fingerprints of large-scale neuronal interactions. *Nature Reviews Neuroscience*, 13(2), 121–134 <https://doi.org/10.1038/nrn3137>
- Silva-Pereyra, J. F, Klarman, L, Lin, L. J. F, & Kuhl, P. K (2005). Sentence processing in 30-month-old children: An event-related potential study. *NeuroReport*, 16(6), 645–648 <https://doi.org/10.1097/00001756-200504250-00026>
- Singer, W (2007). Binding by synchrony. *Scholarpedia*, 2(12), 1657
- Skeide, M. A, & Friederici, A. D (2016). The ontogeny of the cortical language network. *Nature Reviews Neuroscience*, 17(5), 323 <https://doi.org/10.1038/nrn.2016.23>
- Sporns, O (2013). Structure and function of complex brain networks. *Dialogues in Clinical Neuroscience*, 15(3), 247–262
- Stam, C. J, Nolte, G, & Daffertshofer, A (2007). Phase lag index: Assessment of functional connectivity from multi-channel EEG and MEG with diminished bias from common sources. *Human Brain Mapping*, 28(11), 1178–1193 <https://doi.org/10.1002/hbm.20346>
- Varela, F, Lachaux, J. P, Rodriguez, E, & Martinerie, J (2001). The brain-web: Phase synchronization and large-scale integration. *Nature Reviews Neuroscience*, 2(4), 229 <https://doi.org/10.1038/35067550>
- Vigliocco, G, Perniss, P, & Vinson, D (2014). Language as a multimodal phenomenon: implications for language learning, processing and evolution. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369(1651), 20130292
- Weber-Fox, C, Wray, A. H, & Arnold, H (2013). Early childhood stuttering and electrophysiological indices of language processing. *Journal of Fluency Disorders*, 38(2), 206–221 <https://doi.org/10.1016/j.jfludis.2013.01.001>
- Wechsler, D (2002). *WPPSI-III administration and scoring manual*. San Antonio, TX: Psychological Corp
- White, E. J, Nayman, C, Dunkley, B. T, Keller, A. E, Valiante, T. A, & Pang, E. W (2018). Addressing the language binding problem with dynamic functional connectivity during meaningful spoken language comprehension. *Frontiers in Psychology*, 9, 1960 <https://doi.org/10.3389/fpsyg.2018.01960>
- Youssofzadeh, V, Vannest, J, & Kadis, D. S (2018). fMRI connectivity of expressive language in young children and adolescents. *Human Brain Mapping*, 39(9), 3586–3596 <https://doi.org/10.1002/hbm.24196>
- Zhu, Z, Hagoort, P, Zhang, J. X, Feng, G, Chen, H. C, Bastiaansen, M, & Wang, S (2012). The anterior left inferior frontal gyrus contributes to semantic unification. *NeuroImage*, 60(4), 2230–2237 <https://doi.org/10.1016/j.neuroimage.2012.02.036>

How to cite this article: Panda EJ, Emami Z, Valiante TA, Pang EW. EEG phase synchronization during semantic unification relates to individual differences in children's vocabulary skill. *Dev Sci*. 2020;00:e12984. <https://doi.org/10.1111/desc.12984>