



Temporal and topographical changes in theta power between middle childhood and adolescence during sentence comprehension

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ABSTRACT

Time frequency analysis of the EEG is increasingly used to study the neural oscillations supporting language comprehension. Although this method holds promise for developmental research, most existing work focuses on adults. Theta power (4–8 Hz) in particular often corresponds to semantic processing of words in isolation and in ongoing text. Here we investigated how the timing and topography of theta engagement to individual words during written sentence processing changes between childhood and adolescence (8–15 years). Results show that topographically, the theta response is broadly distributed in children, occurring over left and right central-posterior and midline frontal areas, and localizes to left central-posterior areas by adolescence. There were two notable developmental shifts. First, in response to each word, early (150–300 msec) theta engagement over frontal areas significantly decreases between 8 and 9 years and 10–11 years. Second, throughout the sentence, theta engagement over the right parietal areas significantly decreases between 10 and 11 years and 12–13 years with younger children's theta response remaining significantly elevated between words compared to adolescents'. We found no significant differences between 12 and 13 years and 14–15 years. These findings indicate that children's engagement of the language network during sentence processing continues to change through middle childhood but stabilizes into adolescence.

1. Introduction

Quickly and accurately retrieving individual word meanings and integrating them into an ongoing sentence is a complex skill that children are generally able to perform quickly and seemingly effortlessly at quite young ages (Fernald et al., 2001; Hirsh-Pasek and Golinkoff, 1996; Lew-Williams and Fernald, 2007; Swingley et al., 1999; Valteau et al., 2018). However, behavioral studies indicate significant improvements in the speed and efficiency of semantic retrieval over the course of the school years (Hurks et al., 2006; Mahler and Chenery, 2019). Recent findings using time frequency analysis of the EEG indicate that changes in neural oscillations, specifically within the theta frequency (4–8 Hz), support semantic aspects of sentence comprehension in adult populations (Bastiaansen et al., 2002; Lam et al., 2016; Maguire et al., 2010; Mellem et al., 2013; Hagoort et al., 2004). Neural oscillations are a beneficial way to investigate how brain development supports changes

in the speed and efficiency of semantic retrieval because they provide temporally precise insights about interneuronal communication that are not available with behavioral measures, fMRI, or traditional Event Related Potential (ERP) analysis (Cohen, 2014; Maguire and Abel, 2013; Kiellar et al., 2014; Singer, 2011). In particular, traditional ERP analyses often result in the removal of important non-stimulus locked changes in oscillatory activity, thus limiting what can be reflected by the EEG. Analysis of neural oscillations maintains these non-stimulus locked changes. These benefits are highlighted by a recent study of sentence processing in school-aged children which uncovered developmental differences in the theta response but not in the N400 response (Schneider and Maguire, 2018). Identifying how the neural processes supporting semantic retrieval change over the course of the school years may provide a new window into how and why behavioral differences occur during this developmental time period.

Theta engagement occurs in response to a range of cognitive tasks,

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however, the relationship between theta and word retrieval in adults is well established. A significant increase in theta power is observed in response to individual words in isolation, word pairs, and sentences (Bastiaansen et al., 2005; Bastiaansen et al., 2008; Bastiaansen and Hagoort, 2015; Bastiaansen et al., 2008; Meyer, 2018; Hald et al., 2006; Schneider et al., 2016, 2018; Lam et al., 2016; Schneider and Maguire, 2018). Indeed, this theta power increase is larger to pseudowords than real words (Klimesch et al., 2001a, 2001b) indicating that it corresponds to the process of retrieving semantic meaning from memory, becoming larger when retrieval is more difficult. Additionally, related to sentence processing, increases in theta power have been associated with aspects of semantic unification (Hagoort et al., 2004; Schneider et al., 2018). Semantic unification requires the integration and convergence of individual words over the course of the sentence to create a comprehensive message of what is being communicated. Taken together, research in adults highlights the role of theta activation during semantic retrieval and unification.

There is very limited work related to the theta response in children during language tasks. Theta-band entrainment research has shown more automatic and efficient theta responses in response to speech sounds throughout infancy (Attaheri et al., 2021; Ortiz-Mantilla et al., 2016). Evidence from older children indicates that children exhibit theta responses to words in situations quite similar to adults, including individual word retrieval (Krause et al., 2001; Spironelli and Angrilli, 2010), incongruent word pairs (Fernández et al., 2012), and incongruencies in sentences (Schneider and Maguire, 2018; Spironelli and Angrilli, 2010), but there is increasing evidence that the amplitude (Schneider and Maguire, 2018) and topography (Schneider et al., 2018; Spironelli and Angrilli, 2010) of these effects change with age. For example, children demonstrate an increase in theta in response to individual words that is larger over anterior and posterior locations through age 10 compared to adults (Spironelli and Angrilli, 2010). Similarly, Schneider et al. (2018) reported that over the course of naturally-paced, grammatically correct sentences, 10–12-year-olds demonstrate a sustained theta increase distributed over frontal and right fronto-central areas that is not observed in adults; however, in the study the neural responses were not time locked to individual words. Thus, across a variety of language tasks, these findings indicate that the neural and cognitive systems supporting semantic retrieval might not be fully developed by at least age 12.

These findings also highlight how limited our knowledge is concerning the specific temporal and topographic neural underpinnings of sentence processing in children. In addition to evidence that the power and topographical distribution of theta are more sensitive to development differences than the N400 (Schneider and Maguire, 2018), the N400 latency is notoriously stable (Kutas and Federmeier, 2011). As a result, subtle differences in temporal processing may be difficult to uncover with the N400. An in-depth study of timing of theta engagement in response to words may provide a more nuanced understanding about how the temporal aspects of word retrieval change in the school years. Better understanding of the topography and timing of differences between younger and older children in theta engagement while processing words within semantically congruent sentences will lay the foundation for future work, such as studying children with language disorders using this powerful methodology.

The current study therefore aims to clarify differences in the timing and topography of theta engagement between middle childhood and adolescence during meaning retrieval and semantic unification in a visually presented, word-by-word sentence processing task. Children ages 8–15 years completed a word learning from context task and a short battery of vocabulary and reading assessments. Here, we focus on the processing of individual words in a sentence to clarify theta engagement during grammatical sentence processing. We predict that theta engagement will be more widespread in younger children as they will actively recruit a larger language network to complete the task than adolescents. Additionally, we anticipate developmental differences in the timing of theta engagement at the single word level during sentence

processing. Further, we will address whether any of the developmental differences we uncover may also be accounted for by changes in vocabulary and reading abilities that occur between middle childhood and adolescence.

2. Methods

2.1. Participants

Participants included 150 children ages 8–15 years of age. These participants were selected from a larger study of 275 participants so there would be a near equal number of participants per age group. For our 4 age groups (8–9 years, 10–11 years, 12–13 years, 14–15 years) we found that 14–15-year-old consisted of the smallest number of participants ($N = 38$). We selected the first 38 participants run on the study for each age group for the current analysis. Within this set, 2 participants had to be removed for having too few usable trials. For analyses, the data included into four age groups: 8–9-year-olds ($M = 9.01$ years, $SD = 6.4$ months, $N = 37$ (19 males)), 10–11-year-olds ($M = 11.06$ years, $SD = 6.3$ months, $N = 38$ (10 males)), 12–13-year-olds ($M = 12.89$ years, $SD = 7.5$ months, $N = 38$ (19 males)), and 14–15-year-olds ($M = 14.76$ years, $SD = 6.6$ months, $N = 37$ (17 males)). All participants were right-handed children with no history of significant neurological issues (traumatic brain injury, CVA, seizure disorders, history of high fevers, tumors, or learning disabilities) or medications other than over-the-counter analgesics, as per parent and self-report. All children were English dominant and reported being in an English-only classroom at school. No parent reported their child as having a history of reading disability or developmental language delay or disorder. In children, typical reading (word-level and comprehension) and receptive vocabulary were confirmed with the Test of Word Reading Efficiency-Second Edition (TOWRE; Torgeson et al., 2012), Gray Oral Reading Tests (GORT; Wiederholt and Bryant, 2012), and Peabody Picture Vocabulary Test – 4 (PPVT-4; Dunn and Douglas, 2007), respectively. Information pertaining to standardized scores on these assessments can be found in Table 1.

2.2. Stimuli

For the EEG task, participants completed an experimental word learning task, which included a total of 300 sentences, presented as 100 sets of three sentences (sentence triplets). All sentences ended with a pseudoword, serving as a noun. In half of the sentence triplets, the pseudoword served as the word to be learned; the other half of the sentence triplets introduced the pseudoword with no support for learning. The task was for the children to infer what the unknown pseudoword might mean using the preceding information in the sentence. Example stimuli are provided in Table 2.

Information related to the word learning task can be found in other papers (Abel et al. 2018; Maguire et al., 2018; Ralph et al., 2020; Schneider et al., 2021). For this study, we focused on how children processed the words in the sentences leading up to the unknown word. The sentences were simple, active sentences 6–9 words in length. The pseudoword was always last and was always preceded by either an article (*a, an, the*) or possessive pronoun (*my, your, his, her, their*). This study focused on processing words embedded in the sentence so analyses included data from words 2, 3 and 4 (see Table 3 for specifics). Because we wanted to ensure that all children knew and could read all of the

Table 1
Behavioral assessment average performance by age group.

Age Group	PPVT-4 Mean (SD)	GORT Mean (SD)	TOWRE Mean (SD)
8–9-year-olds	108.54(14.92)	95.83(11.03)	98.32(12.19)
10–11-year-olds	109.68(17.59)	100.97(17.44)	104.63(11.85)
12–13-year-olds	111.13(13.92)	102.24(24.27)	99.26(27.61)
14–15-year-olds	107.00(13.68)	101.12(13.40)	102.12(12.52)

Table 2

Example stimuli.

Example sentences with pseudoword in italics
Her parents bought her a <i>pav</i> .
The sick child spent the day in his <i>ziv</i> .
Her favorite toy of all time is the <i>thut</i> .

Table 3

Information about the words used as stimuli for words 2, 3, and 4.

Measures	Word 2	Word 3	Word 4
Age of Acquisition (months) in production	23.7 (4.06)	23.3 (11.95)	24.1 (4.2)
Standard Frequency Index	60.9 (9.50)	61.9 (10.77)	63.3 (10.39)
Word length (letters)	4.93 (1.83)	4.76 (1.87)	4.68 (1.83)
Word length (syllables)	1.36 (0.58)	1.32 (0.59)	1.34 (0.58)
Word class (Percentage)			
Noun	34.0%	31.0%	26.0%
Verb	44.0%	39.0%	40.0%
Adjective	12.0%	9.0%	9.0%
Adverb	2.0%	5.0%	7.0%
Pronoun	4.0%	6.0%	6.0%
Preposition	0.0%	5.0%	8.0%
Conjunction	1.0%	2.0%	2.0%
Determiner	3.0%	4.0%	2.0%

words used in the task, the words selected for this sentence were considered early-appearing words, with the majority appearing either in the MacArthur-Bates Communicative Development Inventories (Fenson et al., 2006) or in a corpus of words spoken by 4- and 5-year old children (Hall et al., 1984). In Table 3, the age of acquisition is calculated as the age at which 50% of children produce that word (Fenson et al., 2006). Frequency was determined based on the Standard Frequency Index (Carroll et al., 1971).

2.3. Procedure

To perform the word learning task, children sat in a chair 1 m from a computer monitor. They were told that they would read sets of three sentences with a pseudoword as the last word in each sentence. Sentences were presented word-by-word with each word appearing for 500 ms and a blank screen between words appearing for 300 ms.

All procedures were in accordance with the IRB at the University of Texas at Dallas. Participants were accompanied by a parent or guardian and were tested individually in the lab. After a short introduction period the parent and child completed the consent and assent forms. The EEG task and reading and language assessments were counterbalanced to avoid having the results of one task or the other systematically influenced by fatigue.

2.4. EEG acquisition

EEG was collected from 64 silver/silver-chloride electrodes mounted within an elastic cap (Neuroscan Quickcap), which are placed according to the International 10–20 electrode placement standard (Compumedics, Inc.). EEG data were recorded continuously using a Neuroscan SynAmps2 amplifier and CURRY software sampled at 1 kHz with impedances typically below 5 k Ω .

2.5. EEG pre-processing

Data were recorded with the ground at Fz and the reference electrode located near the vertex, resulting in small amplitudes over the top of the head. To eliminate this effect, data were re-referenced offline to the average potential over the entire head, approximating the voltages

relative to infinity (Nunez and Srinivasan, 2005). Data was low-pass filtered at 80 Hz, high-pass filtered at 0.1 Hz, and re-sampled to 500 Hz. Bad electrodes and blocks of data containing muscle activity/artifacts were removed from the continuous EEG data by using the artifact subspace reconstruction plug-in within EEGLab (Mullen et al., 2015; Chang et al., 2018). To remove additional ocular and muscle artifacts data was decomposed using an Independent Components Analysis (ICA; Delorme and Makeig, 2004; Delorme et al., 2001), and non-cortical components were automatically identified and removed using the multiple artifact rejection algorithm (MARA) plug-in (Winkler et al., 2011; Winkler et al., 2014). MARA is a supervised machine learning algorithm that learns from expert ratings of 1290 components across the spatial, spectral and the temporal domain, which allows for the identification of patterns of muscle and ocular movement in the data.

After ocular and muscle artifact removal, data were epoched from 500 msec before to 3600 msec after the presentation of the first word in the sentence. As a result, the 500 msec prior to the onset of the first word in the sentence was used as the baseline for all analyses. This timing was selected because 3600 msec aligns with the end of the presentation of word 4. This ensured the exclusion of the last word, which was the pseudoword, and the word before the last word, which was always either an article (*a*, *an*, *the*) or possessive pronoun (*my*, *your*, *his*, *her*, *their*). A semi-automatic artifact rejection procedure was applied to reject epochs containing data with amplitudes $\pm 75 \mu\text{V}$. The analysis included an average of 262.97 (SD=48.14) trials per participant for 8–9-year-olds, 280.95 (SD=48.95) for 10–11-year-olds, 291.21 (SD=18.99) for 12–13-year-olds and 284.31 (SD=44.63) for 14–15-year-olds.

2.6. Time frequency analysis

Time frequency analysis was used to quantify event-related spectral perturbations (ERSP) using the EEGLab toolbox of Matlab (Mathworks, Inc.). The mean ERSP was computed for all data channels between 3 and 30 Hz and a complex Morlet wavelet analysis was applied to each epoch to measure the amount and phase of the data in each successive, overlapping time window, beginning with a 2-cycle wavelet. To control the shape of the individual time and frequency windows, the number of cycles in the wavelets used for higher frequencies continued increasing linearly by 5 cycles. Therefore, a wavelet width ranging from 2.5 to 4.5 cycles was applied to our frequency range of interest (4–8 Hz). This interval was averaged across all trials, within each condition, and the mean baseline power at each electrode and frequency was subtracted so that power differences revealed are relative to baseline (Delorme and Makeig, 2004). A window of 3–30 Hz was selected to ensure no muscle artifacts in higher frequencies influenced the ERSP data, while also ensuring the height of the theta-frequency waves did not attenuate or change shape due to an overly aggressive low-pass filter. For our analyses, we used the adult theta-band limits of 4–8 Hz. This was based on the fact that the individual peak amplitude of theta computed in children ages 10–12 parallels that of adults during a sentence comprehension task (Schneider et al., 2018).

To control for the multiple comparisons problem, we computed a cluster-based test statistic within the Fieldtrip toolbox of EEGLab (Oostenveld et al., 2011). This is done by first comparing every sample (channel, frequency, time) within each experimental condition using a t-test. All samples whose t values were significant at an alpha of .05 are clustered into connected sets, based on their temporal, spatial, and spectral adjacency. The cluster-level statistics were then calculated by taking the sum of the t-values within every cluster and determining the maximum cluster-level statistic. To then determine statistical significance between groups we applied the Monte Carlo method. Using the cluster-based test statistic identified by the previous analysis, the Monte Carlo permutation involves: 1. Collecting EEG data for each of the experimental conditions, 2. Drawing as many trials from each combined data set as there are conditions and placing these additional trials within separate subsets (referred to as random partitioning) and 3. Calculating

the test statistic based on this random partition (i.e. the maximum of the cluster-level summed t-values). Steps 2 and 3 are repeated 1000 times, based on data size and number of variables, then random test statistics are compared to the observed test statistic. The permutation *p*-value is the proportion of partitions where the observed test statistic is larger than the value drawn from the permutation test statistic. Permutation accuracy can be quantified by means of the well-known confidence interval of its binomial distribution (Ernst, 2004; Maris and Oostenveld, 2007).

3. Results

3.1. Topographical distribution of theta power across all ages

To identify developmental differences in the topographical distribution of the theta response while children process words in an ongoing sentence we calculated the average theta amplitude (4–8 Hz) for the time period spanning the onset of the second word to the end of the fourth word. We separated this window into the 500 msec time periods when the words appeared on the computer screen (word) and the 300 msec when the screen was blank between words (blank). All of the time periods were baseline corrected to the 500 msec prior to the onset of the first word in the sentence. We then computed an ANOVA comparing the theta response of the 4 age groups (8–9, 10–11, 12–13 and 14–15-year-olds) for each word and blank window using the Monte Carlo cluster correction analysis described above.

As seen in Fig. 1, this analysis resulted in significant broadly distributed differences across age groups over nearly all areas of the scalp for words 2, 3, and 4 as well as smaller between-word differences during processing of blanks over right parietal areas. Notably, left central and parietal areas did not exhibit differences. This analysis indicates two important things: (1) increases in theta are sensitive to the process of word retrieval and (2) the theta response becomes smaller and more localized with age. To better visualize how these theta changes occur over the course of the sentence we computed theta power for each 25 msec time period from the onset of the sentence to the end of the presentation of word 4 for each channel. We then averaged across these channels in clusters representing the midline frontal, left and right central and parietal-occipital areas (see Fig. 2).

While Fig. 2 does not provide any statistical comparisons, it provides a visualization of changes in the theta response over the course of the sentence, confirming the patterns observed in Fig. 1. Notably younger children exhibit a larger broadly distributed increase in theta power in

response to each word that continues for a longer time period and in some cases fails to return to baseline levels between words especially over right central parietal areas. As such, this figure provides further evidence of the need for more fine-grained temporal analyses of topographical patterns in the theta response to identify developmental trends.

To further clarify when during the course of processing a word theta responses occur, following Schneider et al. (2018), we performed the cluster-correction analysis described above with a sliding window of 25 ms over from the onset of word 2 to the end of word 4. Omnibus one-way ANOVA tests were computed to identify changes in the topographical distribution of the theta response between all ages. By applying this sliding window, we were able to observe more fine-grained differences in timing. To avoid type 1 errors, we focus primarily on differences that: (1) are found in the omnibus test presented in Fig. 1, (2) occur in at least 2 of the 3 words (word 2, word 3, and word 4), (3) occur in clusters of at least 4 electrodes, and (4) occur over at least 3 consecutive 25 msec time periods.

As Fig. 3(a-c) show, words 2, 3, and 4 appear to be quite similar in terms of the timing of theta engagement differences between age groups. Over the course of each word, there are significant differences over right central parietal areas, which continue in the time between words, though to a lesser degree. Between approximately 150 ms and 375 ms the topographical distribution of the theta group differences broadens to include nearly the whole scalp, with the exception of left central areas. Supporting and expanding upon the earlier findings, these results appear to be driven by younger children engaging increased theta power for a longer period of time over a more broadly distributed network than older children for each of the words examined here.

3.2. Topographical distribution of theta power between age groups

The omnibus one-way ANOVAs in Fig. 3a-c identify clear and robust differences between age groups in the topography of theta engagement over the course of individual word presentation and, although broad patterns seem to emerge, the analyses are unable to statistically identify the age at which topographical and temporal differences occur. To delve into this question, we performed posthoc t-tests comparing age groups to identify when clear differences in the topographic distribution exist. This analysis further specifies the omnibus findings by more clearly identifying the developmental time periods that are driving them.

As shown in Fig. 4, significant differences in middle childhood (8–9 versus 10–11-year-olds) were greatest around 250 msec after word onset. The amplitude of the theta response was greater and more widespread in 8–9-year-old children, specifically over right fronto-central electrodes. As shown in Fig. 5 in late childhood/early adolescence (10–11 versus 12–13-year-olds) differences were greatest during earlier sentence processing, at words 2 and 3. During early sentence processing (word 2), 10–11-year-old children had a greater theta response over fronto-central electrodes and, throughout the course of the sentence, they demonstrated a greater theta response over right parietal electrodes as compared to 12–13-year-old children. There were no significant differences between 12 and 13 and 14–15-year-olds (not pictured).

3.3. Relationship between theta and vocabulary and reading

The analyses above indicate two clear developmental time periods when there are notable and distinct changes in the topography of the theta response. The first is between 8 and 9 and 10–11 years over midline frontal areas around 200 msec after the onset of each word. The second is between 10 and 11 and 12–13 years over right parietal areas. The timing of this second effect appears most robust between words but as a result carries over into the processing of the words (when compared to the pre-sentence time period). While these changes are clearly related to age because that is how the groups were defined, it is unclear if the

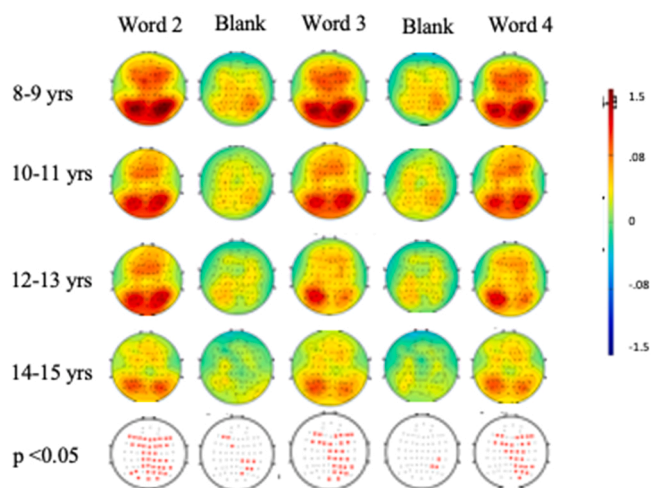


Fig. 1. Topographical distribution of theta power during word presentation (500 msec) and between words (300 msec). The figure indicates increases (red/yellow) and decreases (blue) in theta power during words 2–4.

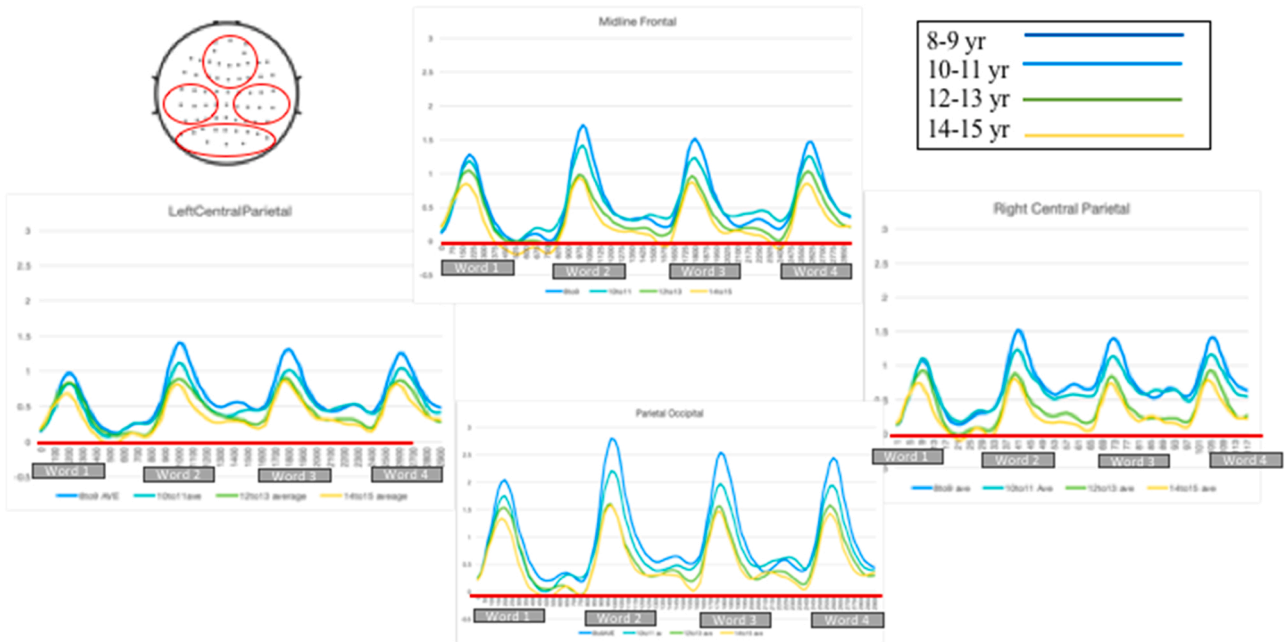


Fig. 2. A comparison of theta power over the course of the full sentence for each age group, over 4 regions.



Fig. 3. a. Word 2 age group differences in the topographical distribution of theta power. The figure indicates increases (red/yellow) and decreases (blue) in theta power in 25 msec bins.

driving factor that results in these changes is due to maturation (age) or differences in language-related abilities, namely vocabulary and reading, which are also improving significantly over these time periods.

To test whether differences in vocabulary and reading predict these theta differences beyond the influence of age we performed two partial correlations to identify whether developmental theta changes correlated with performance on the standardized assessments of receptive vocabulary (PPVT) and reading (GORT as an index of reading comprehension, and TOWRE as an index of word-level reading efficiency) when controlling for age.

First we analyzed the relationship between theta over right fronto-central areas and vocabulary and reading in children 8–11 years old when controlling for age in months, we calculated the mean theta amplitude for the time period between 175 and 275 msec for words 2, 3 and 4 for the 7 channels that most consistently resulted in significant age differences (F6, F8, FC4, FC6, Cz, C2, and C4) between 8 and 9 and 10–11-year-olds. We then performed a partial correlation between right fronto-central theta, vocabulary, reading comprehension, and reading efficiency controlling for age in months. We found no significant correlations between the theta effect over right fronto-central areas and any

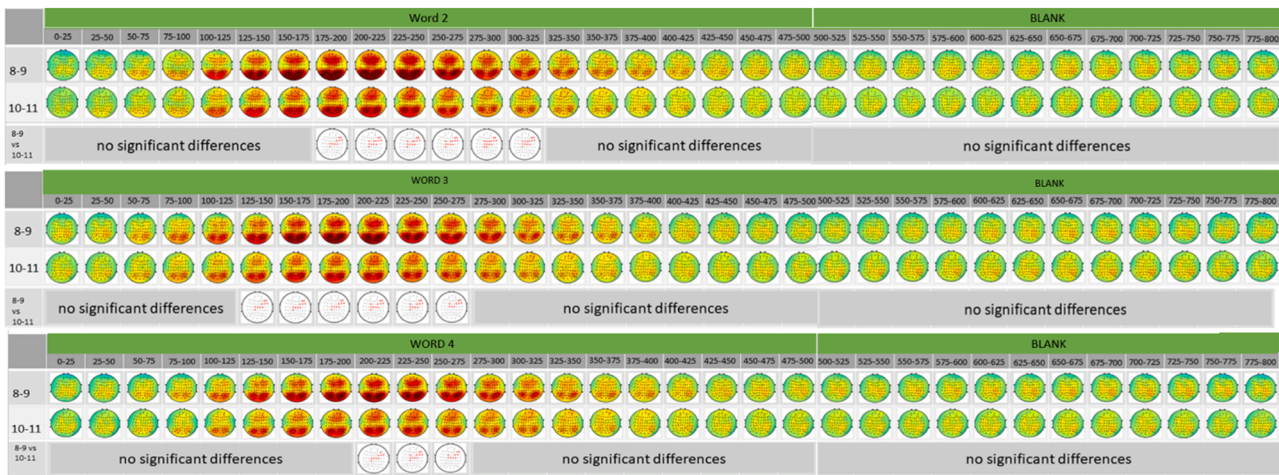


Fig. 4. Post hoc age group comparisons of 8–9-year-olds and 10–11-year-olds. The figure indicates increases (red/yellow) and decreases (blue) in theta power between groups over the course of words 24 in 25 msec bins.



Fig. 5. Post hoc age group comparisons of 10–11-year-olds compared to 12–13-year-olds. The figure indicates increases (red/yellow) and decreases (blue) in the theta power between groups over the course of words 2–4 in 25 msec bins.

of the standardized assessments.

Similarly, to identify if vocabulary and reading contributed to the differences observed over right parietal areas between ages 10–13-year-olds, we calculated the mean theta amplitude for the time period from the onset of the second word to the end of the fourth word for the 9 channels that most consistently revealed age differences (Cp2, Cp4, Cp6, P2, P4, P6, PO4, PO6, O2). Within these time periods we separated out the theta response related to the 500 msec period when the word was on the screen and the 300 msec period between words when the screen was blank. We found that, when controlling for age in months, theta power during the blank window was positively correlated with TOWRE ($R = 0.285, p = 0.016$), but no other significant correlations were found between the theta effect over right parietal areas for the time between words and our other assessments (PPVT and GORT), or the time period during word presentation and our vocabulary and reading assessments.

4. Discussion

This is the first paper to study differences in the timing and topography of the theta response supporting word retrieval during sentence processing between middle-childhood and adolescence. We found that the theta response to known words within a sentence context is topographically more broadly distributed in children, localizing to left

central areas by adolescence. This is in line with previous findings comparing the theta response related to words in isolation (Spironelli and Angrilli, 2010) and during sentence processing between children and adults (Schneider et al., 2018). More detailed analyses of the temporal differences underlying our findings of broad topographical changes between middle childhood and adolescence uncovered a significant decrease in early theta power over frontal areas between ages 8–9 and 10–11 (Fig. 4) and a significant decrease in more temporally sustained theta power over right parietal areas between 10 and 11 and 12–13-year-olds (Fig. 5). Interestingly, there were no significant differences observed between 12 and 13 and 14–15-year-olds, suggesting that, by this age, language networks may have reached a point in development similar to those of adults. Based on the timing of these theta responses, and previous literature linking theta to semantic retrieval in adults (Bastiaansen et al., 2005; Bastiaansen et al., 2008; Bastiaansen and Hagoort, 2015; Bastiaansen et al., 2008; Meyer, 2018; Hald et al., 2006; Schneider et al., 2016, 2018; Lam et al., 2016; Schneider and Maguire, 2018), we interpret the developmental differences observed here as indicative of semantic retrieval and more broadly developmental changes in the underlying language network. These findings add mounting evidence to previous arguments (Brauer and Friederici, 2007; Friederici et al., 2011; Schneider et al., 2016, 2018) that children engage a language network that is structurally and functionally different than

adults.

One difficulty in studying age-related differences in the neural oscillations underlying language comprehension is that multiple aspects of age-related development may play a role in the changes that are observed. Specifically, there are three known developmental changes that could be driving the differences we uncovered: (1) changes in resting state neural oscillatory activity, (2) maturation of the neural structure supporting the neural oscillations, and (3) improvements in children's language and reading abilities. Resting state EEG within the theta band exhibits developmental changes in the age range we studied (Campbell and Feinberg, 2009; Cellier et al., 2021; Perone et al., 2018) however, we contend that those shifts would not explain the topography and power differences evoked here. While the relationship between resting state and task evoked processes is complex and still under debate (Bolt et al., 2018), by baseline correcting the data we tried to offset some of these potential differences. As a result, we feel that the changes observed in our data are likely driven primarily by brain maturation and changes in language abilities. We draw this conclusion because increased localization, and more specifically, decreased right hemispheric activation during language tasks occurs as a function of increasing age across a range of methodologies (Brauer and Friederici, 2007; Friederici et al., 2011; Holland et al., 2007; Szaflarski et al., 2006; Xiao et al., 2016). More localized and lateralized language processing is dependent on the development of increased functional connectivity between frontal and posterior areas of the left hemisphere (Friederici et al., 2011). In relation to the current study, it appears that this functional development is relatively mature by around age 12.

The claim that maturation accounts for the majority of the differences observed in this study is supported by the fact that, when controlling for age, the age-related differences observed in the right frontal region were not correlated with our measures of vocabulary, reading comprehension, or reading efficiency. Indeed the only relationship we did observe between the theta response and our vocabulary and reading measures was an unexpected positive correlation between theta over right parietal areas during the 300 msec between words and word-level efficiency in children ages 10–13. This could reflect increased semantic unification processes in children with superior word-level reading skill, as children in 5th–8th grades (corresponding to ages 10–13) are transitioning from word level reading to reading comprehension in school. Maintaining theta engagement not just during word processing, but between words to unify them, likely maps onto similar skills demanded for reading comprehension. Future research designed specifically for this question is necessary to explore this relationship. It is important to note that our correlation findings do not mean there are not changes in theta engagement that occur in relation to improvements in vocabulary and reading; instead, the differences observed in this study, identified when comparing across ages, cannot be attributed primarily to changes in vocabulary and reading and thus are likely due to maturation more than language. Future studies may specifically seek to identify language-related changes that are not driven by maturation.

In adults, we see variations in the distribution of theta in language studies related to the demands of the task, specifically differentiating word retrieval from semantic unification. Increases in theta over left posterior and left temporal regions, the regions that show the greatest consensus across age groups in the current study, occur in response to words in isolation (Bastiaansen et al., 2005) as well as words in sentences (Bastiaansen et al., 2002; Lam et al., 2016; Bastiaansen et al., 2005). The timing (generally between 300 and 500 msec after word onset) and location of these theta responses in the current study align with research in adults demonstrating increases in theta during the process of retrieving of information from long-term memory (e.g., Burgess and Ali, 2002; Klimesch et al., 2001a, 2001b, 2008, 2010; Burgess and Gruzeller, 2000; Klimesch, 1999). As a result, the left central-parietal theta response is thought to reflect the process of word retrieval (Bastiaansen et al., 2005). Based on this interpretation our findings indicate that the theta response underlying word retrieval is

relatively stable from age 8 through 15.

In contrast to the stability of the theta response over left posterior and temporal areas, we observed robust developmental differences over bilateral frontal and right parietal regions, which in adults seem to be more specific to sentence processing and have been associated with semantic unification (Bastiaansen et al., 2005; Schneider et al., 2018). Semantic unification is defined here as increased working memory load to integrate individual words throughout the sentence and converge them into a comprehensive understanding of what is being communicated. Memory research has demonstrated similar increases in theta at frontal and parietal sensors with increasing working memory load and active maintenance of items in memory (Cashdollar et al., 2009; Deiber et al., 2007; Jensen and Tesche, 2002). In regard to the limited existing developmental research, it appears that widespread theta responses during a syntactic judgement task in children as compared to adults has been interpreted as a greater reliance on semantic unification as opposed to syntactic unification processes (more often observed in the beta frequency; Schneider et al., 2016, 2018). Younger children's (8–9-year-olds) greater reliance on theta over right central parietal areas in the current study may therefore reflect increased processing demands related to semantic unification. This interpretation is supported by the fact that the effects over right parietal areas seem to be related to the theta response failing to return to baseline levels between words for younger children compared to older children.

Similar developmental differences in the distribution and duration of the N400 in response to semantic violations have been reported and related to children's age and/or vocabulary skill (e.g., Khalifian, 2016; Schneider and Maguire, 2018; Panda et al., 2021). While informative, the N400 is calculated at the single word level in many of these studies, limiting our understanding of how differences at the word level manifest over the course of the entire sentence. Of the few studies which have examined developmental differences in theta engagement over the course of a sentence, many focus on processing demands surrounding semantic anomalies (Schneider and Maguire, 2018; Panda et al., 2021), and fail to examine whether differences in theta band engagement exist based on retrieval versus unification processes (Schneider et al., 2016). Building on these past studies, we were able to pinpoint two unique ways in which theta activation occurred, and how the localization and timing of these two responses varied, as a function of age. In the current study, we only focus on a few words in the context of very short sentences. While we feel confident this comparison captures the beginning stages of sentence processing, the patterns of theta differences seen in the three words do not differ to a large extent. We believe that an in-depth study into how the processing of each word might differ over the course of the sentence would require longer, more complex sentences. We speculate that later sentence processing effects would amplify differences in semantic unification as working memory load builds; however, future work is needed to clarify this question.

Because this task uses written stimuli presented one word at a time, we have introduced the additional task demands of reading to the word learning task. As described, we tried to limit the influence of reading ability by using only early-acquired words in relatively simple sentences, but the fact that children are not as fluent in their reading as adults cannot be overlooked as a possible explanation for some of our findings. Thus, future work will need to address if and how reading ability influences developmental differences in theta engagement during language comprehension tasks. One other potential limitation is the lack of a non-lexical control condition. Given the past research on the relationship between semantic processing and the theta response, we feel our interpretation of the data is sound (Bastiaansen et al., 2005; Bastiaansen et al., 2008; Bastiaansen and Hagoort, 2015; Bastiaansen et al., 2008; Meyer, 2018; Hald et al., 2006; Schneider et al., 2016, 2018; Lam et al., 2016; Schneider and Maguire, 2018), however such a control may provide new insights about this relationship.

Investigating theta oscillations during sentence comprehension can further inform our understanding of the processes underlying lexical

retrieval and semantic unification. While extensive research has been conducted in adults, our knowledge of how task-based theta engagement changes across the course of development remains relatively understudied. In the current study we provide evidence that theta engagement at left central-parietal regions, associated with lexical retrieval, is stable by age 8; however, theta responses across bilateral frontal and right parietal regions, more commonly associated with higher level semantic unification processes, continue to develop through age 12. By better isolating the developmental trajectory of the neural oscillations supporting unique aspects of sentence comprehension, we can begin to pinpoint how individual differences in these trajectories influence academic, cognitive, and social outcomes during the school years.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The scripts that support the findings of this study are available from the corresponding author upon reasonable request. All data are available on the Open Science Framework: <https://osf.io/z38rb/>.

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