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Developmental differences in the neural oscillations underlying auditory sentence processing in children and adults

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ABSTRACT

Although very young children seem to process ongoing language quickly and effortlessly, neuroimaging and behavioral studies reveal that children continue to mature in their language skills through adolescence. During this prolonged development, children likely engage the same basic cognitive processes and neural mechanisms to perform language tasks as adults, but in somewhat different ways. In this study we used time frequency analysis of EEG to identify developmental differences in the engagement of neural oscillations between children (ages 10–12) and adults while listening to naturally-paced sentences. Adults displayed consistent beta changes throughout the sentence compared to children, thought to be related to efficient syntactic integration, and children displayed more broadly distributed theta changes than adults, thought to be related to more effortful semantic integration. Few differences in alpha, related to verbal working memory, existed between groups. These findings shed new light on developmental changes in the neuronal processes underlying language comprehension.

1. Introduction

Real-time language comprehension is a fast-paced, complex task that includes retrieving and integrating phonological, semantic, syntactic, and pragmatic information with millisecond precision. Behavioral and neuroimaging research indicate that the development of adult-like language abilities and the neural structures underlying those abilities is quite prolonged, continuing through age 12 or later (e.g., Atchley et al., 2006; Friederici & Hahne, 2001; Holland et al., 2007; Nunez et al., 2011). While older children seem to perform well on everyday language tasks, they exhibit subtle errors or processing differences when language capabilities are taxed, indicating children may engage somewhat different skills or strategies than adults (Holland et al., 2007).

Many theories have noted that the prolonged development of language skills may be related to the successful development of effective and efficient semantic integration, syntactic integration, and working memory (e.g., Brauer & Friederici, 2007; Chou et al., 2006; Just & Carpenter, 1992; McDonald, 2008); skills that play an essential role in adult language processing (Bastiaansen & Hagoort, 2006; Boudewyn, Long, & Swaab, 2013; Just & Carpenter, 1992; Nakano, Saron, & Swaab, 2010). Supporting these claims, Event Related Potential (ERP) studies report that semantic and syntactic abilities continue to develop through early adolescence (e.g., Atchley et al., 2006; Friederici & Hahne, 2001; Hahne & Friederici, 1999; Holcomb, Coffey, & Neville, 1992). In these studies, participants read or hear sentences that contain a semantic or grammatical error. Children and adults exhibit a larger N400 to semantic errors and a larger P600 to grammatical errors. While specifics vary across studies, the general finding is that children display an N400 that is later, larger, and more broadly distributed and a P600 that is later and larger compared to adults. These differences are thought to indicate slower and less automatic semantic and syntactic processes, reflecting higher cognitive demands related to semantics and syntax when children perform the same task as adults. Because this method is based on responses to violations, ERPs are somewhat limited in what they can reveal about processing everyday, grammatically correct spoken language (Maguire & Abel, 2013).

Recent studies of the neural oscillations underlying language processing using EEG and MEG have provided new insights related to adults' processing of natural language that is grammatically and semantically correct (Bastiaansen & Hagoort, 2006; Lam, Schoffelen, Uddén, Hultén, & Hagoort, 2016; Maguire & Abel, 2013; Meyer, Obleser, & Friederici, 2013; Weiss & Mueller, 2003). Using time frequency analysis of the EEG and MEG signals one can identify changes in

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the amplitude, or power, of the response within each frequency of interest during a language task. A power increase is thought to relate to additional neural assemblies firing at the same frequency and a power decrease is thought to correspond to fewer neurons firing within that frequency (Nunez & Srinivasan, 2006). As such, time frequency analysis provides a more direct measure of neural processing and can reveal changes in the EEG that are unobservable with traditional ERP analysis. In adults, changes in neural oscillations have been linked to a range of cognitive-linguistic processes based on the task the participants perform. Of particular interest here are theta, alpha, and beta, each of which exhibit reliable changes in response to specific aspects of sentence processing in adults; though to date we know little about how these processes change with development. Below, we will briefly review the literature relating each frequency band to adult sentence processing, then will offer predictions for children.

During sentence processing, increases in theta power correspond to semantic integration, increasing most when integrating new semantic information with the preceding context is difficult (Bastiaansen & Hagoort, 2006; Davidson & Indefrey, 2007; P Hagoort, Hald, Bastiaansen, & Petersson, 2004; Hald, Bastiaansen, & Hagoort, 2006; Maguire, Brier, & Ferree, 2010; Wang, Zhu, & Bastiaansen, 2012). For example, Bastiaansen, van Berkum, and Hagoort (2002) and Bastiaansen, Magyari, and Hagoort (2010) found that theta increased with each new word in a sentence. Further, the theta power increase was significantly greater at the point of a semantically incongruent word compared to congruent word, indicating increased processing demands.

Changes in the beta frequency band have been related to syntactic integration during sentence processing, as evidenced by increases in beta with each word in a grammatically correct sentence (Bastiaansen et al., 2010; Davidson & Indefrey, 2007; Meyer et al., 2013). Importantly, beta increases when reading correctly formed sentences but not word lists (Bastiaansen et al., 2010) and decreases in response to a syntactic error (Bastiaansen et al., 2010; Davidson & Indefrey, 2007). Thus, similar to the N400 and P600 ERP responses, theta and beta play different roles in sentence processing with theta indexing semantic integration and beta indexing syntactic integration. However, unlike ERP components, theta and beta show predictable sustained changes during grammatically correct sentence processing.

Changes in alpha often relate to working memory engagement during verbal and non-verbal tasks (see Klimesch, Freunberger, Sauseng, & Gruber, 2008 for a review). Specific to sentence processing, Meyer et al. (2013) studied EEG changes as adults listened to sentences differing in how many words intervened between the subject of a verb and the verb. Alpha power increased during the sentence but the increase was greater for sentences with more intervening words, which was attributed to the increased working memory demands. There is substantial literature noting the impact of working memory on sentence processing in children and adults (Boudewyn et al., 2013; Just & Carpenter, 1992; McDonald, 2008; Montgomery, Magimairaj, & O'Malley, 2008; Nakano et al., 2010), suggesting developmental differences in the effective and efficient engagement of working memory during language processing.

To date, the vast majority of the work studying changes in neural oscillations during sentence processing has focused on adults. Only one study has addressed changes in neural oscillations in children when processing syntactic errors (Schneider, Abel, Ogiela, Middleton, & Maguire, 2016). In that study 10–12 year olds displayed a significantly less pronounced decrease in beta power during error processing and a smaller, later P600 effect compared to adults. Interestingly, children also demonstrated a significant increase in theta and an apparent N400 effect during processing of the syntactic error, which was unexpected and not observed in adults. This finding supports previous theories that semantics and syntax are largely overlapping in how they are processed in childhood (Hahne, Eckstein, & Friederici, 2004; Skeide, Brauer, & Friederici, 2014). Specifically, that children rely more heavily on semantic information when processing syntactic errors than adults. What remains unclear is if these developmental differences are solely related to grammatical error processing, or if there is a developmental shift in processing of grammatically correct language in which children exhibit a greater dependence on semantic processing while adults exhibit a greater dependence on grammatical processing.

If it is the case that children rely more heavily on semantic information to process naturally paced, grammatically and semantically correct language than adults, we would expect a developmental shift in the engagement of theta and beta, such that over the course of a sentence children will exhibit a more broadly distributed and larger theta increase than adults and adults will exhibit larger and more consistent beta changes. On the other hand, if sentence processing is simply more effortful for children than adults, we would expect children to exhibit increases in alpha power as well. To test these predictions we used time frequency analysis of EEG to examine changes in the theta, beta and alpha underlying naturally-paced auditory sentence comprehension in 10–12 year old children and adults.

2. Methods

2.1. Participants

Twenty-three right-handed, monolingual English-speaking adults ages 18–31 (9 male, 14 female; $M = 24$ years, $SD = 4.3$ years) and sixteen right-handed, monolingual English-speaking children ages 10–12 years (8 male, 8 female; $M = 10.88$ years, $SD = 0.96$ years) participated in the study. Adults completed the Edinburgh Handedness Inventory (EHI). To screen for handedness in children, parents were surveyed about their child's hand preference. To confirm the parental report, children completed the EHI in which they perform a variety of tasks that determine hand preference (opening a screw top bottle, throwing a ball). All participants had no history of significant neurological issues (traumatic brain injury, CVA, seizure disorders, history of high fevers, tumors, or learning disabilities), based on adult self-report and children's parental report. Exclusion criteria included left-handedness, use of alcohol or controlled substances within 24 h of testing, and medications other than over-the-counter analgesics and birth control. Adults gave written consent to participate, and for children, parental consent and child assent was obtained, all in accordance with the Institutional Review Board of The University of Texas at Dallas. This study was conducted according to the Good Clinical Practice Guidelines, the Declaration of Helsinki, and the U.S. Code of Federal Regulations. Parents and children received a $25 gift card for their participation and adults received course credit.

2.2. Stimuli

The data presented here come from a larger study examining EEG processing of grammatically correct and incorrect sentences (Schneider et al., 2016). Sentences written for this study were manipulated for complexity (simple/compound), number (singular/plural), and grammaticality (grammatical/ungrammatical). Example stimuli are presented in Table 1. The complexity manipulation was included to increase the signal-to-noise ratio and control for an expectancy effect. The number manipulation was included to counterbalance effects of omission and intrusion for the ungrammatical task. This study focuses on processing of grammatical stimuli; details about the creation and EEG processing of the ungrammatical stimuli are included in Schneider et al. (2016). Sentences were created to be easily processed by children and as such were comprised of words found in children's early vocabularies (Fenson et al., 1994). They varied in length (3.6–4.6 s) to avoid expectancy and wrap-up effects and to remain naturalistic. (see Table 2).

Critical to this study is the target noun-verb pairing, which contained information about both number and grammaticality. Notably, the compound sentences contained two noun-verb pairings; for this