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Developmental differences in beta and theta power during sentence processing

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ABSTRACT

Although very young children process ongoing language quickly and effortlessly, research indicates that they continue to improve and mature in their language skills through adolescence. This prolonged development may be related to differing engagement of semantic and syntactic processes. This study used event related potentials and time frequency analysis of EEG to identify developmental differences in neural engagement as children (ages 10–12) and adults performed an auditory verb agreement grammaticality judgment task. Adults and children revealed very few differences in comprehending grammatically correct sentences. When identifying grammatical errors, however, adults displayed widely distributed beta and theta power decreases that were significantly less pronounced in children. Adults also demonstrated a significant P600 effect, while children exhibited an apparent N400 effect. Thus, when identifying subtle grammatical errors in real time, adults display greater neural activation that is traditionally associated with syntactic processing whereas children exhibit greater activity more commonly associated with semantic processing. These findings support previous claims that the cognitive and neural underpinnings of syntactic processing are still developing in adolescence, and add to them by more clearly identifying developmental changes in the neural oscillations underlying grammatical processing.

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-level precision. Behavioral and neuroimaging research indicate that the development of adult-like language abilities and the neural structures underlying those abilities is prolonged, continuing through age 12 or later (Atchley et al., 2006; Friedrich and Friederici, 2004; Friederici and Hahne, 2001; Silva-Pereya et al., 2005; Nuñez et al., 2011). Performing well during natural, everyday language tasks but exhibiting subtle processing differences when language capabilities are taxed indicates that children may engage somewhat different skills or strategies than adults during language comprehension (Holland et al., 2007). To better understand the nature of these differences we used event-related potentials (ERPs) and time frequency analysis of EEG to examine the neural oscillations underlying naturally paced sentence comprehension in children and adults.

Many theories have noted that the development of effective semantic integration and syntactic unification may contribute to the prolonged development of language skills (e.g., Brauer and Friederici, 2007; Chou et al., 2006). One must quickly retrieve semantic representations related to each incoming word and then, as each new word in the sentence is encountered, integrate it to form a coherent semantic representation. For example, when hearing the phrase *the hairy*, it is easier to integrate the word *dog* with that phrase than *table*, because *a hairy dog* refers to a logical semantic representation in a way that *a hairy table* does not. Syntactic unification is also necessary for successful language comprehension. Continuing our example, in English, adjectives are often followed by nouns; thus, one can integrate the syntactic information in *the hairy dog* to form a meaningful representation but not *the hairy eat*.

Research using ERPs consistently reports that semantic and syntactic abilities develop through early adolescence to support language comprehension (e.g., Atchley et al., 2006; Friederici and

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Hahne, 2001). Participants in these studies read or hear sentences containing a semantic error (She buttered her toast with a *dress*) or a grammatical error (The goose was in the *fed*). Compared to correct sentences, children and adults exhibit a larger N400 to semantic errors and a larger P600 to grammatical errors. Although study specifics vary, children generally display an N400 that is later, larger and more broadly distributed and a P600 that is larger and later compared to adults (Benau et al., 2011; Friederici and Männel, 2013; Hahne et al., 2004; Friedrich and Friederici, 2004; Friederici, 2006). These developmental differences are thought to reflect higher cognitive demands when children perform the same language task as adults. These findings are informative about the development of early language skills but, due to the process of averaging the EEG signal to produce an ERP, non-phase locked dynamics, providing important information related to semantics and syntax, can be lost. Recent computational advances, such as time frequency analysis, provide different means of analyzing EEG data by decomposing the signal to identify changes in the amplitude, or power, of the response within frequency bands of interest (Davidson and Indefrey, 2007; Cohen, 2014). Given this advantage, time frequency analysis may identify differences in processing that are lost due to the averaging process used in traditional ERP analysis.

Changes in the beta frequency band (12–30 Hz) have been related to syntactic unification (e.g., Bastiaansen et al., 2010; Davidson and Indefrey, 2007). According to theories of syntactic unification, each incoming word in a sentence activates multiple syntactic possibilities, called lexical frames (Vosse and Kempen, 2000). These lexical frames specify the potential structural environment for each incoming word, and are combined based on various features and constraints to create one stable syntactic structure by which the meaning of the sentence can be decoded. Related to time frequency analysis, beta increases with each word in a visually presented grammatically correct sentence, but decreases at the point of a syntactic error in a sentence, when syntactic unification fails (Bastiaansen et al., 2010; Davidson and Indefrey, 2007). Further, when the words of a sentence are presented in a random order, no increase in beta occurs, presumably due to the lack of syntactic information (Bastiaansen et al., 2010). Although beta responds differently to a syntactic violation than the P600 ERP component, both appear to play an important role in identifying changes in syntactic processing.

Similar to beta, theta power also increases with each word during sentence reading (Bastiaansen et al., 2010). However, at the point of a semantically incongruent word in the sentence, theta power is greater than when the words are semantically congruent. Similar to the N400, the amount of theta increase may be linked to how difficult it is to semantically integrate the current information with the preceding context (Davidson and Indefrey, 2007; Hald et al., 2006). However, to date, no research that we know of has studied the neural oscillations underlying the semantic aspects of sentence processing in children compared to adults.

While theta and beta increase during reading of sentences, they diverge in how they respond to an error in the sentence - theta increases to a semantic error whereas beta decreases to a syntactic error (Bastiaansen et al., 2002, 2010). On the surface, it seems that theta and beta are similar to the N400 and P600 ERP responses, indexing semantic integration and syntactic unification, respectively; however, further research is needed to identify the relationship between language processes and underlying neural activity. The current study uses ERP (e.g., P600, N400) and time frequency (e.g., theta, beta) analyses to investigate neural processing in children 10–12 years old and adults during a grammaticality judgment task in which they listen to sentences containing either no grammatical error or a verb agreement error (e.g., she *walk*). For both groups, we predicted theta and beta increases for grammatically correct sentences and a beta decrease/P600 effect following the agreement error. We examined the possibility of a theta increase/N400 because children seem to engage different strategies than adults during language processing. Further, we performed analyses to better identify the relationships between ERPs, changes in power, and behavioral measures.

2. Methods

2.1. Participants

Eighteen right-handed, monolingual English-speaking adults ages 18–31 (9 male, 9 female; $M = 24.41$, $SD = 4.37$) and eighteen right-handed, monolingual English-speaking children ages 10–12 years (9 male, 9 female; $M = 10.94$, $SD = 0.94$) participated in the study. 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 parental report for child participants. 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 contraceptives.

2.2. Stimuli

Participants completed a grammaticality judgment task in which they heard a sentence and indicated via button press whether the sentence was grammatical or ungrammatical. Each sentence began with a prepositional phrase followed by either a plural (we/they) or singular (he/she) pronoun subject followed by an action verb (e.g., jump; jumps) with all words in the sentence found in children's early vocabularies (Fenson et al., 1994). In ungrammatical sentences, the grammatical violation was a noun–verb agreement error occurring at the verb (e.g., *he walk*, *they walks*). Importantly, the current study design utilizes verb forms with and without the morphological ending –*s*. Both conditions were equally likely to occur in both the grammatical and ungrammatical conditions, therefore eliminating differences in processing the acoustical properties of the word as a confounding variable. Sentences were either simple (one critical noun–verb pairing) or compound (two critical noun–verb pairings). To ensure that participants were fully engaged in the process of sentence parsing before the onset of the critical verb, and to avoid interference of wrap-up effects at the sentence-final position, there were at least three words preceding the pronoun and critical verb, and at least two words following the critical verb (Hagoort et al., 1993). Ungrammatical compound sentences contained only one ungrammatical phrase; two grammatical violations never occurred in the same sentence. Example sentences can be found in Table 1. To create the auditory stimuli, grammatically correct sentences were recorded by a female native English speaker using typical intonation. A splicing technique, using Cool Edit Pro 2.1 (Adobe Systems Inc.), was applied to create all ungrammatical sentences from the recorded

Table 1
Examples of grammatical sentences. All sentences began with a prepositional phrase and were followed by the critical noun–verb pairing, which are underlined in the above examples. Simple sentences contained one critical noun–verb pairing while compound sentences contained two.

	Singular	Plural
Simple	In the gym he jumps higher than me	In the gym they jump higher than me
Compound	In the gym he jumps high but they jump higher.	In the gym we jump high but he jumps higher.